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EFFECTS OF DESIGN AND OPERATING VARIABLES ON NOx FROM COAL-FIRED FURNACES. PHASE II

W. Joseph Armento

Babcock and Wilcox Company

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February 1975

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16. ABSTRACT The report gives results of Phase II of an investigation of combustion modification techniques for controlling NOx emissions that have application to pulverized coal-fired utility boilers. The techniques, studied on a 5 million Btu/hr single-burner pilot unit, included: excess air, air preheat, firing rate, flue gas recirculation, staged combustion, quench, and swirl. Phase II tests, conducted with a Colorado coal, showed that NOx reductions of up to 65% were possible by using staged combustion or by lowering excess air levels from 30 to zero %. Flue gas recirculation yielded only moderate NOx reductions for coal. For existing units, control of excess air appears to be the simplest method for NOx reduction. Where possible, staged combustion could be retrofitted on existing units to achieve further NOx reductions. For new units, staged combustion combined with low excess air firing appears to be the most promising method for NOx control.

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by

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Prepared for

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ABSTRACT

The purpose of this contract was to investigate various combustion modification techniques for control of NO_x which might find application on pulverized coal-fired boilers.

The laboratory tests were made on a single burner coal-fired test unit. The techniques studied were: (1) excess air, (2) air preheat, (3) firing rate, (4) flue gas recirculation, (5) staged combustion, (6) quench, and (7) swirl. Natural gas, No. 6 oil and two coals were used in the tests.

For coal combustion, reductions of up to 65% in NO emission levels were observed using staged combustion. Reduction of excess air from 30 to 0% yielded similar results. Flue gas recirculation reduced NO by a small amount, but apparently only thermally formed NO is reduced.

Fuel nitrogen conversion increases with increasing excess air. At substoichiometric conditions, the final precursors for NO formation from either fuel bound nitrogen conversion or thermal atmospheric fixation are identical.

For existing units, control of excess air appears to be the simplest method for NO_x reduction. In addition, when possible staged combustion on existing units could be used to achieve further NO_x reductions.

For new units, staged combustion combined with low excess air firing appears to be the most promising method of NO_x control.

This report was submitted in fulfillment of Contract No. 68-02-0634 by The Babcock & Wilcox Company under the sponsorship of the Environmental Protection Agency. Work was completed as of October 31, 1974.

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The results of this phase of the contract are due to the efforts of others as well at the Alliance Research Center. In particular, W. L. Sage and C. L. Wagoner were responsible for administrative help; E. D. Scott and F. M. Holsopple were responsible for furnace operation; and E. W. Stoffer, J. M. Kibler, and F. M. Holsopple were responsible for instrumentation.

F. M. Holsopple also contributed to two Appendices and Figures in Section II.

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SYMBOLS AND ABBREVIATIONS

This list of symbols and abbreviations is included so that all items in the text may be easily interpreted. All air weights and measurements are calculated dry unless otherwise noted. All items without specific units are used in a "general" form of descriptive equation not requiring numerical calculation.

Symbol, Abbreviation	Definition
A	Pre-exponential rate constant
Aver	The average of two measurements
BTU	Fuel enthalpy release, BTU/hr
BTU_a	Air enthalpy, BTU/lb
BTU_f	Flue gas enthalpy, BTU/lb
BTUG	Total enthalpy release in furnace, BTU/hr
BTU_m	Humidity (in air) enthalpy, BTU/lb of air
d	Differential
D_1	Diameter of orifice, inches
D_2	Diameter of pipe, inches
e	Natural constant
E	Activation energy
f	Subscript indicating forward
FB	Fraction of total air at burner
FCO2	Fraction of CO_2 in flue gas
FGR	Flue gas recirculation, %
FH2O	Fraction of H_2O in flue gas
k	Kinetic rate constant
L_1	Measured value #1, base point
L_1'	Standard deviation on base point measurement
L_2	Measured value #2, reduced point
L_2'	Standard deviation on reduced point measurement
L_3	Calculated reduction
L_3'	Standard deviation of calculated reduction
MA	Moles of stoichiometric air/lb fuel

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SYMBOLS AND ABBREVIATIONS (Continued)

Symbol, Abbreviation	Definition
MAI	Moles of stoichiometric igniter air/lb igniter fuel
MAR	Moles of stoichiometric test air/lb test fuel
MC	Moles of CO_2 in flue gas/lb fuel
MCI	Moles of CO_2 in igniter flue gas/lb igniter fuel
MCR	Moles of CO_2 in test flue gas/lb test fuel
MF	Moles of flue gas/lb fuel
MFI	Moles of igniter flue gas/lb igniter fuel
MFR	Moles of test flue gas/lb test fuel
MM	Moles of moisture in flue gas/lb fuel
MMF	Moles of moisture from the fuel
MMH	Moles of moisture from the air humidity
MMI	Moles of moisture in igniter flue gas/lb igniter fuel
MMR	Moles of moisture in test flue gas/lb test fuel
n	Temperature exponential in kinetic rate expression
NDIR	NO measurement from the NDIR instrument, ppm Also used for Beckman "Nondispersive Infrared"
NF	Fraction of full meter flow for natural gas igniter
NO	Nitric Oxide*
NO_2	Nitrogen dioxide
NO_x	A mixture of NO and NO_2
N_2	Nitrogen*
O_2	Oxygen*
PB	Barometric pressure, atm
PBA	Percent of stoichiometric air at burner

---

*This symbol in brackets; i.e., [NO], indicates the concentration of that gas. The units on concentration terms as used in calculations in this report are ppm (parts per million); ordinarily, the symbols are used only in descriptive equations not requiring numerical calculations.

SYMBOLS AND ABBREVIATIONS (Continued)

Symbol, Abbreviation	Definition
P_{H_2O}	Partial pressure of H_2O in atmosphere, atm
P_{net}	Total pressure on orifice, atm
POF	Percent oxygen measured in flue gas, corrected for combustibles
PS	$P_{net} - P_{H_2O}$, atm
PT	$PB - P_{H_2O}$, atm
PTA	Percent stoichiometric (theoretical) air
r	Subscript indicating reverse
R	Gas constant
R-N	Specified an organic fuel bound nitrogen molecule
STDV	Standard deviation of Aver
t	Time
T	Temperature of orifice, ^oF; also used as kinetic temperature for any reaction
TA	Ambient temperature, ^oF
TAG	Air preheat temperature, ^oF
TECo	NO measurement from TECo instrument, ppm; also used for "Thermo Electron Corp." chemiluminescence
TFG	Flue gas temperature, ^oF
TM	Total moles/lb fuel
Total	Subscript designating sum of all partial concentrations
W	Weight of gas flow, lb/hr
W_a	Weight of air input to furnace, lb/hr
W_f	Weight of fuel input to furnace, lb/hr
W_{fg}	Weight of flue gas from furnace, lb/hr
W_{fg}'	Weight of recycled flue gas, lb/hr
W_N	Weight of natural gas flow, lb/hr
W_{NI}	Weight of natural gas flow in igniter, lb/hr

SYMBOLS AND ABBREVIATIONS (Continued)

Symbol, Abbreviation	Definition
W_2	Weight of air through second stage, lb/hr
x	Subscript of variable type indicating any combination; i.e., r, l, etc.
ΔH	Differential pressure across orifice, inches H_2O
1,2,3...	Subscript indicating reaction number for partial value

I. INTRODUCTION

A. Objectives of the Contract

The primary objective of this contract was to investigate on an experimental coal fired furnace, a variety of combustion techniques which could be applicable for control of NO_x and related combustible emissions such as CO, carbon, and hydrocarbons. Additionally, details for defining the critical conditions for application of the most promising combustion control techniques to a single burner furnace were to be provided. Finally, the most successful techniques for pollution control in the burning of coal were to be optimized and potential problems in boiler operational and thermal performance were to be identified. The work for the contract was divided into two phases:

Phase I: Identification of the most promising control techniques using a single burner, pulverized coal fired furnace.

Phase II: Definition of the conditions for the most promising techniques as applied to the single burner unit used in Phase I.

The criteria applied to the testing included the degree to which nitrogen oxides were reduced and the effects on thermal and operational performance.

B. Phase I

This phase concentrated on a comparison of the NO_x and combustible emissions from an Ohio coal. Natural gas and a #6 fuel oil were also tested for comparison with the coal. A general comparison of the NO_x control techniques was made. The effects on thermal and operational performance for the application of these techniques were evaluated. The results of the Phase I effort were documented in Final Report EPA-650/2-74-002a.

C. Phase II

The primary objective of this phase was to verify and further define the major variables which were found to influence the formation of NO_x and related combustible emissions in Phase I. A Colorado coal was burned in the single burner, experimental coal fired furnace during Phase II. A comparison of the combustion and NO_x emission characteristics of the Ohio and Colorado coals was also required to determine the general applicability of the control techniques to all utility boiler types which fire coal.

D. Background and Description of Work

The contract work on Phase II was started in July, 1973 and was was completed in July, 1974. A Colorado coal was tested to determine if the same combustion control techniques would control or inhibit NO_x formation to a similar degree as was shown in the Phase I work with the Ohio coal. Additionally the levels of NO_x reduction for both coals were to be compared.

The design and operational variables studied with the Colorado coal were excess air, load, air preheat, staged combustion and port position, port geometry, burner velocity, and to a limited extent, flue gas recirculation. For all test series, except port position and geometry, the variables were changed over a wide range to include both normal operating conditions and extreme operating conditions which would not ordinarily be practical.

A comparison of the two coals was made. The comparison was based on the percent reduction in NO_x emission levels rather than by the absolute change in NO_x emission levels for each control technique.

E. Significant Results of the Phase II Work

It was found that the Colorado coal yielded absolute NO_x emission levels that were as much as 25% greater than the Ohio coal, apparently due to differences in the way fuel bound nitrogen is converted to NO_x. However, the responses of the two coals to the variable trends were similar. Both coals showed about the same percentage reduction in NO_x emission levels over most of the variable ranges.

In the Colorado coal tests, major changes in NO_x emission levels were due to excess air and load. Flue gas recirculation was not effective except at very high levels of recirculation. Staged combustion was the most promising and effective method for NO_x control. Additionally variable port geometry indicated that optimization of the combustion patterns could yield even larger decreases in NO_x. Burner velocity changes had a minimal effect on NO_x emission levels in these tests.

Conversion of fuel bound nitrogen to NO_x was found to increase with increasing excess air. Apparently, the same free radicals are present in the final kinetic step for conversion of fuel bound nitrogen and thermal fixation of atmospheric nitrogen.

The variables studied for both the Ohio and Colorado coals were: 1) excess air, 2) load, 3) preheat, 4) staging, and 5) flue gas recirculation. Both coals showed the same qualitative trends to all of the above five control techniques. There is a distinct quantitative difference in the NO_x emission levels for these two coals: this must be due to the percentage of the fuel bound nitrogen converted to NO since both fuels have the same amount of chemically bound nitrogen.

Both coals and natural gas show an identical relationship between NO_x emission level and total combustion air when fired substoichiometrically. All three fuels show NO_x emissions becoming zero at a total combustion air of 60% of stoichiometric. This would indicate a lower limit of 60% of stoichiometric air for the first stage of a multistage combustion process: no further reduction in NO_x emission levels by reduction of the first stage combustion air would seem practical.

During Phase II, the effects of fineness, port geometry, and burner velocity were determined for the Colorado coal. These control techniques could not be studied for the Ohio coal since major changes were required in our pulverizer or furnace equipment. The time and cost of these changes did not permit more than one change and this was made during Phase II testing of the Colorado coal.

II. APPARATUS

The single burner coal furnace used at the Alliance Research Center is called "The Basic Combustion Test Unit." Adjacent to the furnace is a laboratory area where the instrumentation for stack gas measurements was operated.

A. Description of the Basic Combustion Test Unit

A schematic of the furnace is shown in Figure 2.1. It is of cylindrical construction with a water-cooled jacket and is partially lined with a 1-inch thick refractory brick. The air input at the burner is split into primary (fuel transport) and secondary air flows. The following burner input represents a typical loading of 5,000,000 Btu per hour for single stage combustion:

Primary (fuel transport) — ∿ 15% total air (∿ 500 lb/hr)
500 lb/hr coal
Secondary — ∿ 85% total air (balance of the air or ∿ 3000 lb/hr)

Figure 2.2 is an illustration of the burner used for coal firing. The spinning vanes are fixed with constant swirl applied to the secondary air. The coal spreader at the end of the primary pipe, Figures 2.3 through 2.6, is set at a 45 degree angle of divergence from the centerline to disperse the coal into the secondary air stream.

Figure 2.7 is a photograph of the coal burner hardware (no fuel supply is shown) as it looked before placement in the windbox. In summary, the following configuration was used for firing:

1) Coal – coal burner (6 vaned) for all tests – coal feed pipe carried primary air (∿ 15% total combustion air) for coal transport and had a divergent 45 degree spreader outlet.

2) Natural gas igniter – supplied up to 1% by weight of the fuel and up to 2% of the Btu release rate in furnace. Used about 3 lb natural gas per hour. Used during all coal tests to maintain stable burning, especially for low air and high load.

The positions of the staging ports are illustrated in Figures 2.8 and 2.9. Figure 2.10 is a photograph of the ports which were cut through the furnace. The front slots were set up to admit second stage air from 1-inch by 12-inch inlets parallel to the burner fuel/air feed. The side slots were set up to introduce air into the furnace from 2-inch by 6-inch slots perpendicular to the central axis but offset circumferentially and arranged so that the mixing swirl around the center axis is opposite to the secondary burner swirl. Only one set of second stage ports was operated at one time; both sets were never operated simultaneously.

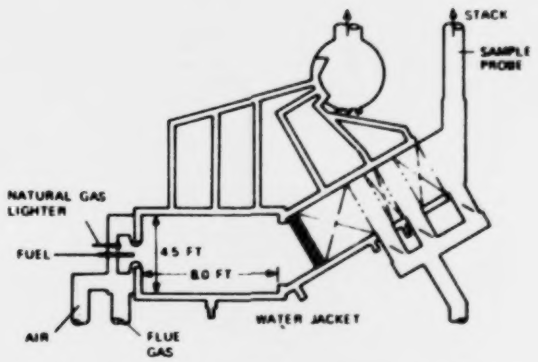
STACK
SAMPLE PROBE
NATURAL GAS LIGHTER
FUEL
4.5 FT
8.0 FT
WATER JACKET
AIR
FLUE GAS

FIGURE 2.1 BASIC COMBUSTION UNIT (SINGLE BURNER)

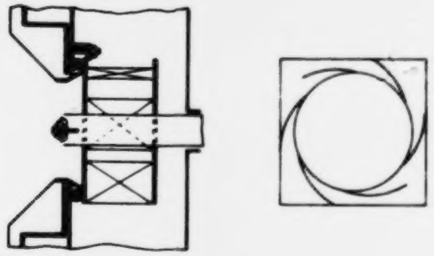

FIGURE 2.2 COAL BURNER

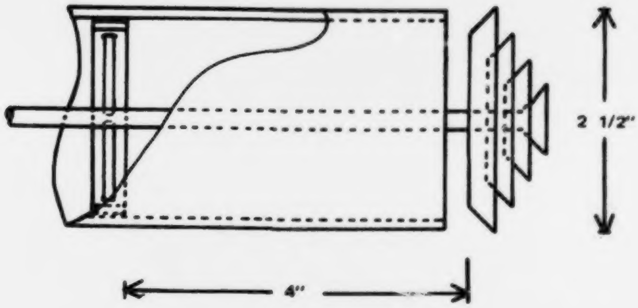

FIGURE 2.3 COAL IMPELLER

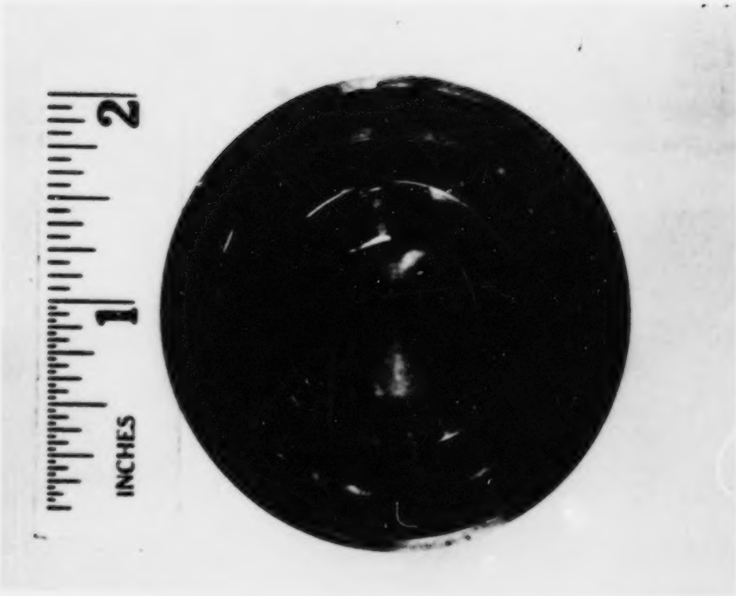

FIGURE 2.4 COAL IMPELLER

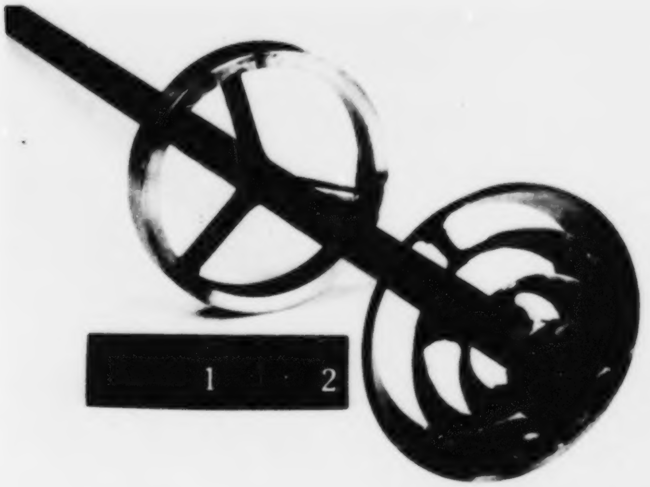

FIGURE 2.5 COAL IMPELLER

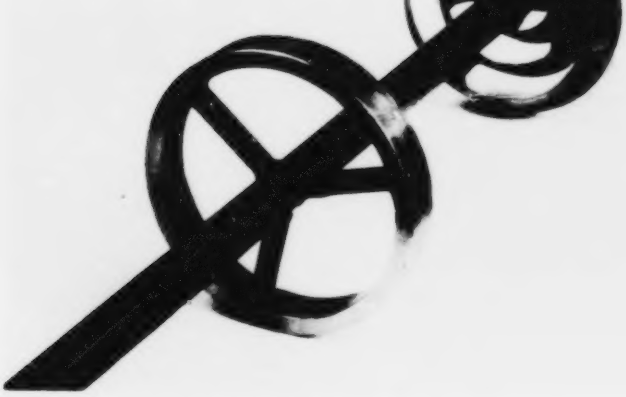

FIGURE 2.6 COAL IMPELLER

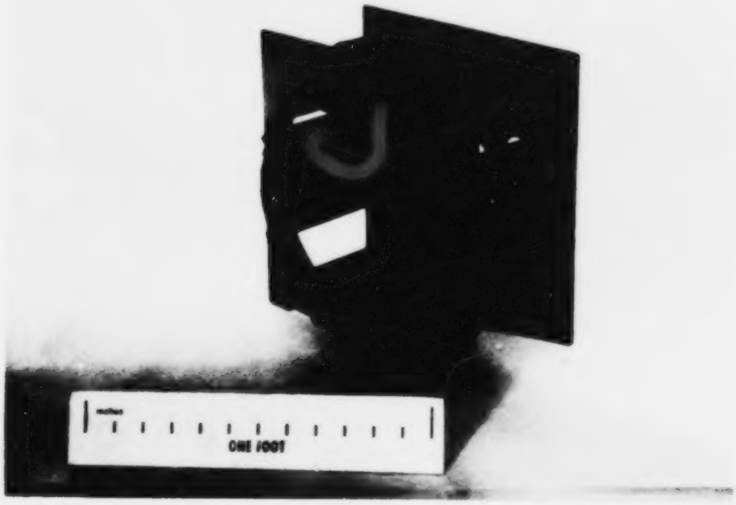

FIGURE 2.7 COAL BURNER ASSEMBLY

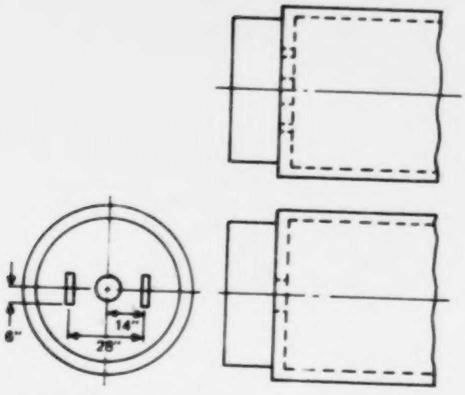

FIGURE 2.8 FRONT SLOT POSITIONS

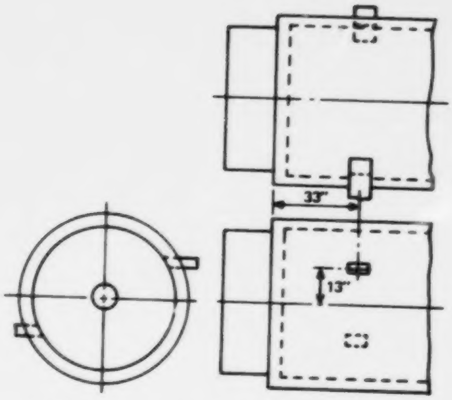

FIGURE 2.9 SIDE SLOT POSITIONS

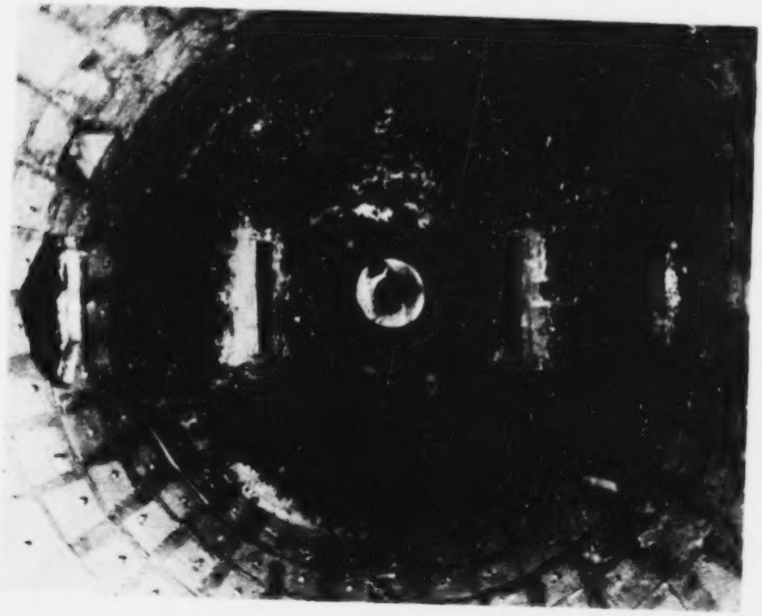

FIGURE 2.10 SLOTS – NO CHANGE

Two changes were made in each set of slots to test the effect of "geometry" of the second stage combustion. The slot geometry for each set of tests is shown below:

1) Base Line (see Figure 2.11)
   Front slots — air entered parallel to burner axis; area of slots 1 x 12 inches.
   Side slots — air entered perpendicular to burner axis on 26-inch diameter circle; area of slots 2 x 6 inches.

(2) First Change (see Figure 2.12)
   Front slots — air entered at a 30 degree inward angle at burner axis; area of slots 1 x 12 inches
   Side slots — air entered perpendicular to burner axis on 13-inch diameter circle, area of slots 3 x 6 inches (50% increase in slot area beyond base line tests)

(3) Second Change (see Figure 2.13)
   Front slots — air entered at a 30 degree outward angle to burner axis; area of slots 1 x 12 inches
   Side slots — air entered perpendicular to burner axis on 13-inch diameter circle, area of slots 4 x 6 inches (100% increase in slot area beyond base line tests)

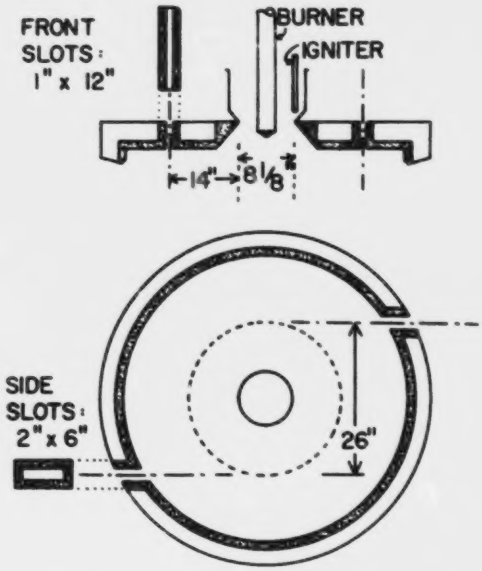
FRONT SLOTS: 1" x 12"
BURNER
IGNITER
14"
8
1/8
SIDE SLOTS: 2" x 6"
26"

FIGURE 2.11 SLOTS – NO CHANGE

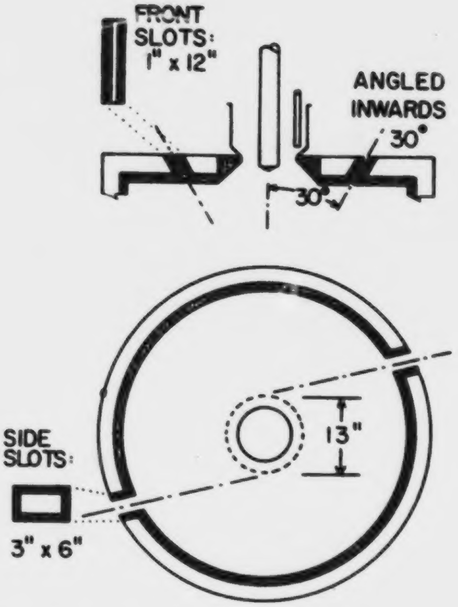
FRONT SLOTS: 1" x 12"
ANGLED INWARDS
30°
30°
SIDE SLOTS:
3" x 6"
13"

FIGURE 2.12 SLOTS – FIRST CHANGE

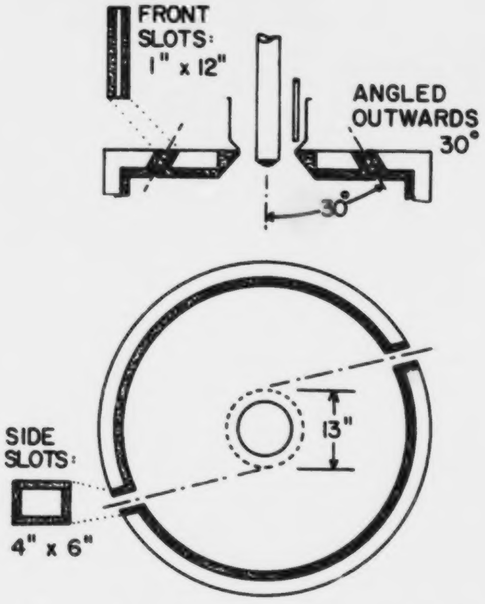
FRONT SLOTS: 1" x 12"
ANGLED OUTWARDS
30°
30°
SIDE SLOTS:
4" x 6"
13"

FIGURE 2.13 SLOTS – SECOND CHANGE

Figures 2.14 and 2.15 illustrate the first change in the front slots and are directly comparable to Figure 2.10.

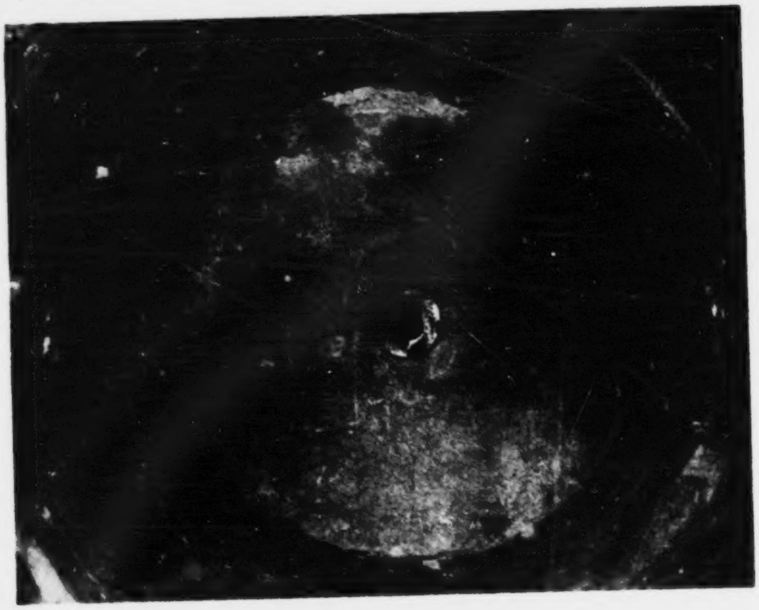

FIGURE 2.14 SLOTS – NO CHANGE

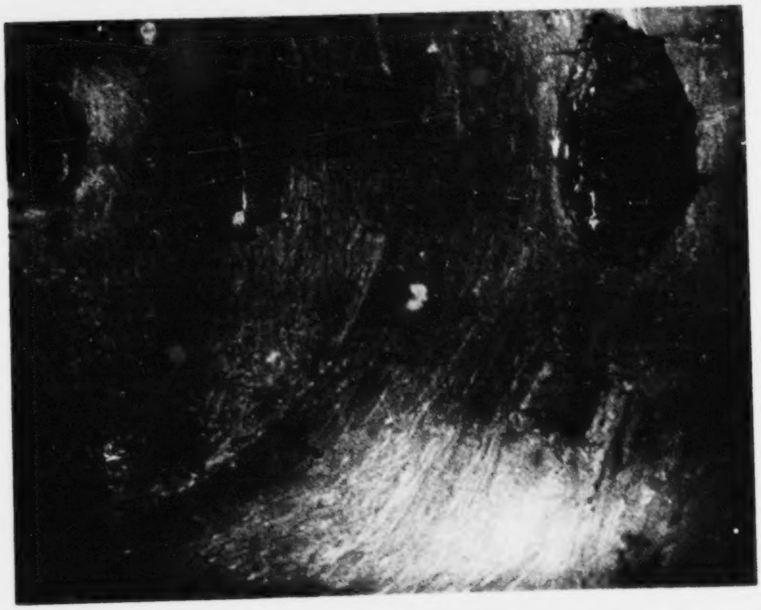

FIGURE 2.15 SLOTS – FINAL CHANGE

B. Furnace and Burner Detail

Figures 2.16 and 2.17 illustrate the details of the furnace and burner cross sections. The impeller position is shown for the coal burner. The coal nozzle exit position is at the beginning of the throat flair.

Burner changes, to study the effect of combustion air burner velocity on NO_x emissions, were made by welding cones of metal into the burner face. Figure 2.18 shows the burner changes that were made to reduce the area by fractions of 1/4 and 1/2. An error of 4% in the calculated area reductions is present because it was thought that the igniter would have to be extended past the burner insert cones to maintain ignition and the area of the igniter was subtracted from the overall area reductions of the throat. Actually, when tested, the flame from the ignition was found to pass smoothly around the inserts and the adjustments to the igniter were not made.

The refractory lining of the furnace is 1-inch brick. The refractory lining extends all around the furnace from the burner to the mid section of the furnace, or a length of 4 feet.

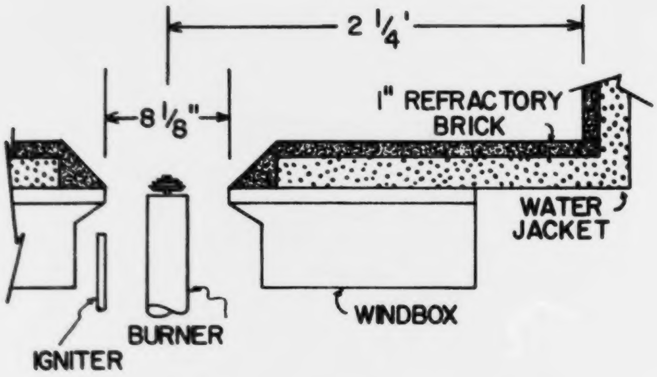

FIGURE 2.16 FURNACE CROSS SECTION

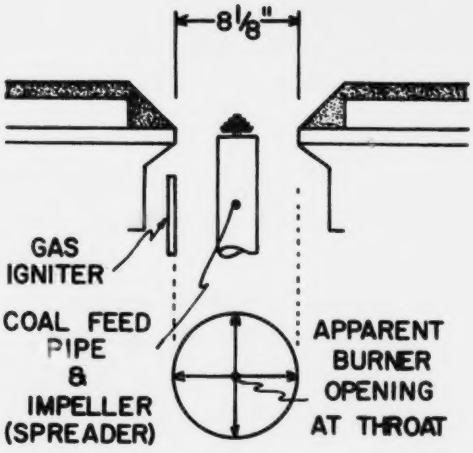
8 1/8"
GAS IGNITER
COAL FEED PIPE & IMPELLER (SPREADER)
APPARENT BURNER OPENING AT THROAT

FIGURE 2.17 BURNER CROSS SECTION

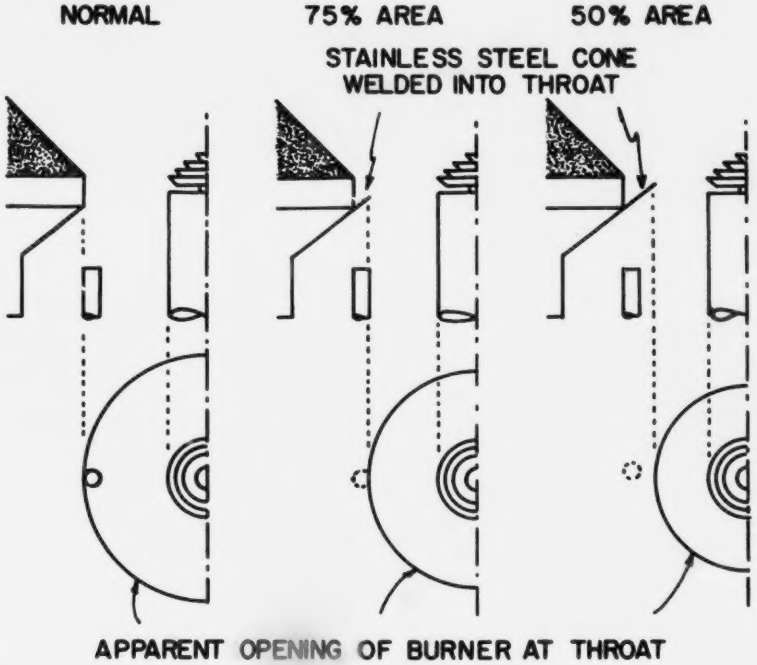
NORMAL
75% AREA
50% AREA
STAINLESS STEEL CONE WELDED INTO THROAT
APPARENT OPENING OF BURNER AT THROAT

FIGURE 2.18 BURNER CHANGES

C. Instrumentation and Sampling

There are two probes in the stack from which gases and ash were regularly taken for measurement. Figure 2.19 shows the probe penetration positions into the stack and the relative position of the gas sampling probe inside the stack during sampling. The first probe was used exclusively for pulling ash samples into a bag filter to determine the ash loading in the gas stream and to provide an ash sample for further analysis. The second probe was used exclusively for gas samples and subsequent measurements.

The instrumentation probe branched into two gas sample lines. The first line carried the gas sample into a pair of Bailey Meter hot-wire analyzers used for measuring O_2 and total gaseous combustibles. The output from these two meters was continually monitored and recorded. The second line carried the gas sample into a 50°F ice bath (see Figure 2.20) before being carried into the instruments. This removed most of the water in the sampled flue gas. The temperature was maintained as closely as possible to 50°F. The gas sample then flowed separately into each of the following instruments:

1) A Thermo Electron Corporation (TECo) chemiluminescence $NO\text{-}NO_2$ monitor

2) A Whittaker NO chemical cell instrument with a Mallcosorb column to remove SO_2, CO_2, and H_2O before NO measurement

3) A Beckman nondispersive infrared (NDIR) NO analyzer with a pretreatment chamber to remove most of the H_2O which interferes in the NO measurement

4) A Whittaker chemical cell SO_2 analyzer

5) An MSA infrared analyzer (LIRA) for CO

6) An MSA paramagnetic O_2 analyzer

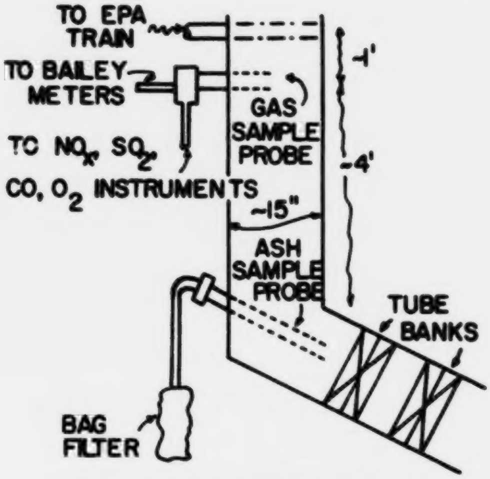
TO EPA TRAIN
TO BAILEY METERS
TO NO_x, SO_2, CO, O_2 INSTRUMENTS
GAS SAMPLE PROBE
~1'
~4'
~15"
ASH SAMPLE PROBE
TUBE BANKS
BAG FILTER

FIGURE 2.19 SAMPLE SYSTEM

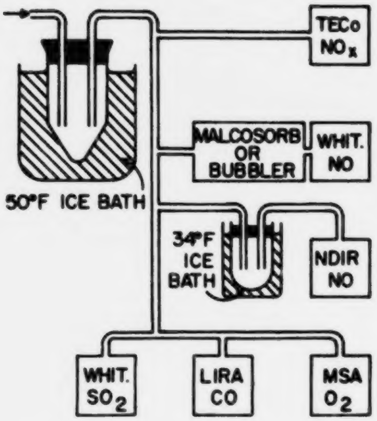
TECo NO_x
MALCOSORB OR BUBBLER
WHIT. NO
50°F ICE BATH
34°F ICE BATH
NDIR NO
WHIT. SO_2
LIRA CO
MSA O_2

FIGURE 2.20 INSTRUMENTATION

All instrumental outputs except for the CO and O_2 analyzers were continuously recorded. The outputs of the CO and O_2 instruments were manually recorded for each test. The 50°F water bath was sufficient for the TECo and the reading of the TECo was unaffected by minor changes of temperature in this bath.

It was found that a 34°F water bath was the only successful treatment for flue gas measurement of NO with the NDIR infrared instrument in the presence of SO_2 and O_2. The temperature of the sample gas in the cold finger was maintained during testing at 34 ± 0.5°F by periodic addition of ice to the water in the bath. The water interference due to the humidity of 34°F saturated flue gas was determined experimentally by bubbling warm air at 70-80°F through water of the same temperature, passing it through the 50°F water bath, and then through the 34°F ice bath, noting condensation of water in the cold finger. The measured interference used to correct all future flue gas measurements was 55 ± 5 ppm NO (the instrument cannot be read to better than ± 5 to 10 ppm NO).

III. PROCEDURES

A day's testing always commenced with the furnace warmup period and instrument calibration. The test series to be carried out in the day's testing started with one or two base line tests at normal operating conditions to verify that everything was operating properly. Testing began only when the furnace, its related systems, and the instrumentation were functioning properly.

The sequence for a test run was to set furnace conditions and check the operation for all instruments. When all equipment and all temperatures were equilibrated to a constant state of firing, the data were taken; first, data were read from nonrecording instruments, and then, data were read off the strip charts for recording instruments on the basis of the time the test was made.

If there were to be comparison tests run in pairs to determine the relative decrease in emissions, both tests were always run together on the same day in order to minimize day-to-day variations.

IV. MEASUREMENTS

A. Variables Studied

There are two types of control (operational and design) that can be used for reduction of NO_x. Operational control techniques are more easily applied to existing units; the physical change on the unit is minimized and the final cost of the change on the unit will be lower. Design methods are best applied to new unit designs to minimize redesign and construction costs. Additionally, it is important to realize that modifications of existing units can be physically impractical or economically unsound.

The design variables, which suggest physical and mechanical changes to a unit, include flue gas recirculation, staged combustion, and basic coal type. The operational variables used on existing units include reductions in excess air, fuel firing rate, and air preheat. These groups of variables are not meant to be mutually exclusive nor totally inclusive. In addition, the geometry of the second stage air addition and the burner air velocity represent important variables.

B. Variable Testing

An attempt was made to hold all conditions constant and to change the one variable under study over a wide range. However, many of the variables are interrelated and thus as load, excess air, preheat, and the other variables were changed, the burner air velocities changed, leading to a variation in mix rate, turbulence, and combustion intensity. No attempt was made to correlate the interactions of all of these variables.

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C. Range of Variables

As each variable was in turn studied, the other variables were held constant. Generally the two extremes and the middle of the range of a variable were tested.

The range of each variable was selected so that the entire practical range of field unit operation could be studied. The extremes of the range were usually outside the practical limits for normal operation of boilers. Conditions have occurred where our basic combustion unit showed unstable combustion tendencies and therefore no meaningful test data could be obtained. Each variable is specifically described under the results.

D. Measurements Taken

The raw flue gas analysis data* taken was: barometric pressure; temperature of the instrument area; oxygen from the MSA; carbon monoxide from the MSA; SO_2 from the Whittaker; and NO from the TECo, Whittaker (no CO_2, SO_2, or H_2O in measured sample), and the NDIR (34°F saturated). For substoichiometric firing, only gas chromatography could be used for carbon monoxide and other combustibles. Ash samples were also taken during some tests and the measurements required were: time, differential pressure, and absolute pressure. An ash sample was removed from the filter bag for analysis of unburned carbon.

The furnace data recorded was: the temperature, and absolute and differential pressures, across a flowmeter or an orifice for each of primary air, secondary air, the second stage air, the flue gas, and the natural gas igniter. The coal feeder rate was also recorded, but was used only as a check for the stoichiometric calculations. Finally, the Bailey oxygen and combustibles meter readings were recorded.

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*Unless otherwise specified, all instrumental flue gas measurements were made at the equivalent of 50°F saturated.

V. PHASE II RESULTS

There were six series of tests run during Phase II. A total of about 200 test points are available. Data are presented in tables in Appendix C, in figures in Appendix D, and the mathematical equations and derivations are in Appendix E.

VI. ANALYSIS OF DATA AND RESULTS

The data in final form are presented in two forms: tables and graphs. The data in the tables were used to prepare all of the graphs which are in this section.

A. Data

The headings for Tables 6.1 to 6.6 are described below:

1) Original Series and Run Numbers – Self explanatory.

2) Total Air, % – The total air added as the percentage of 100% theoretical (stoichiometric) air. The excess air is simply 100% less than this number.

3) Heat, kBtu/ft^3/hr – The overall net heat release rate in the furnace in thousands of Btu per unit volume.

4) Gas Preheat, $^{\circ}$F – Combustion air preheat (this is a weighted average which includes the ambient primary air).

5) Flue Gas Input, % – The weight percentage of flue gas recycled back into the combustion air:

$$\frac{W'_{fg}}{W_a + W_f} \times 100$$

6) Air in Burner, % – The total air at the burner as percent of 100% theoretical (stoichiometric) air. The balance of the air (difference between columns 2 and 6) is the air which entered through the second stage ports.

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7) NO_x, ppm — The NO content of the flue gas corrected to 3% oxygen, dry conditions.

8) CO, ppm — The as measured concentration of CO (and H_2 equivalent as CO) in the flue gas.

9) O_2, % — The as measured (except for combustibles) concentration of O_2 in the flue gas.

TABLE 6.1 BASE LINE TESTS FOR COLORADO COAL (SERIES VII)

SERIES VII - COLORADO COAL

FINAL DATA EVALUATION

ORIGINAL SERIES AND RUN #-S	TOTAL AIR, %	HEAT, KBTU/ FT**3 / HR.	GAS PRE-HEAT DEG F	FLUE GAS INPUT (%)	AIR IN BURNER (%)	NOX PPM	CO PPM	O2 %
VII - 1	113.0	49.59	608	0.0	113.0	953	90	2.7
VII - 2	138.0	50.77	635	0.0	138.0	1250	60	5.8
VII - 3	101.5	48.96	599	0.0	101.5	643	3500	0.5
VII - 4	119.2	30.26	548	0.0	119.2	820	40	3.6
VII - 5	146.2	29.09	570	0.0	146.2	981	40	6.6
VII - 6	105.0	25.15	500	0.0	105.0	510	850	1.1
VII - 7	115.6	66.65	620	0.0	115.6	1085	120	3.1
VII - 8	102.1	47.24	595	0.0	102.1	673	3000	0.6
VII - 9	92.8	46.21	574	0.0	92.8	535	34490	0.2
VII -10	77.4	45.66	542	0.0	77.4	207	95427	0.0
VII -11	72.8	45.66	537	0.0	72.8	104	145000	0.0
VII -12	66.5	45.58	520	0.0	66.5	79	205000	0.0
VII -13	115.0	63.74	622	0.0	115.0	1196	70	3.0
VII -14	140.0	63.19	631	0.0	140.0	1369	60	6.0
VII -15	103.6	56.90	602	0.0	103.6	845	2600	0.9
VII -16	114.9	46.76	296	0.0	114.9	917	150	3.0
VII -17	141.0	45.66	298	0.0	141.0	1102	60	6.1
VII -18	104.6	43.54	285	0.0	104.6	577	2600	1.1
VII -19	115.6	58.40	286	0.0	115.6	945	240	3.1
VII -20	115.0	59.10	290	0.0	115.0	912	115	3.0
VII -21	138.9	56.67	289	0.0	138.9	1042	115	5.9
VII -22	142.0	30.34	285	0.0	142.0	854	60	6.2
VII -23	115.0	28.84	279	0.0	115.0	657	40	3.0
VII -24	104.0	28.22	270	0.0	104.0	443	930	0.9
VII -25	113.6	31.12	556	0.0	113.6	774	375	2.8
VII -26	113.0	52.42	621	0.0	113.0	1064	100	2.7
VII -27	142.0	51.64	637	0.0	142.0	1327	100	6.2
VII -28	136.0	55.02	633	0.0	136.0	1305	150	5.6
VII -29	104.5	48.89	600	0.0	104.5	862	950	1.0

TABLE 6.2 FINENESS TESTS FOR COLORADO COAL (SERIES VIII)

SERIES VIII - FINENESS - COLORADO COAL

FINAL DATA EVALUATION

ORIGINAL SERIES AND RUN #-S	TOTAL AIR, %	HEAT, KBTU/ FT**3 / HR.	GAS PRE-HEAT DEG F	FLUE GAS INPUT (%)	AIR IN BURNER (%)	NOX PPM	CO PPM	O2 %
VIII- 1	115.0	52.97	610	0.0	115.0	1044	80	3.0
VIII- 2	113.7	52.97	615	0.0	113.7	1094	100	2.8
VIII- 3	149.4	53.44	633	0.0	149.4	1309	80	6.9
VIII- 4	102.8	49.91	592	0.0	102.8	727	2150	0.7
VIII- 5	114.3	32.54	551	0.0	114.3	786	150	2.9
VIII- 6	102.9	31.04	530	0.0	102.9	539	1700	0.7
VIII- 7	150.5	33.09	583	0.0	150.5	1143	100	7.0
VIII- 8	114.9	52.50	610	0.0	114.9	1086	150	3.0
VIII- 9	144.1	54.86	629	0.0	144.1	1299	8	6.4
VIII- 10	119.9	51.64	621	22.2	119.9	962	90	3.7
VIII- 11	117.0	61.78	620	0.0	117.0	1226	100	3.3
VIII- 12	115.6	47.63	293	0.0	115.6	856	105	3.1
VIII- 13	143.0	49.20	282	0.0	143.0	1014	90	6.3
VIII- 14	102.7	44.01	270	0.0	102.7	617	475	0.6

TABLE 6.3 FLUE GAS RECIRCULATION TESTS FOR COLORADO COAL (SERIES IX)

SERIES IX - F. G. R. COLORADO COAL

FINAL DATA EVALUATION

ORIGINAL SERIES AND RUN #-S	TOTAL AIR, %	HEAT, KBTU/ FT**3 / HR.	GAS PRE-HEAT DEG F	FLUE GAS INPUT (%)	AIR IN BURNER (%)	NOX PPM	CO PPM	O2 %
IX A - 1	112.4	52.58	615	0.0	112.4	1018	120	2.6
IX A - 2	115.7	36.63	586	0.0	115.7	811	30	3.1
IX B - 3	111.8	53.21	618	6.6	111.8	968	240	2.5
IX B - 4	110.4	53.29	616	18.5	110.4	888	130	2.2
IX B - 5	113.7	38.90	598	22.7	113.7	770	30	2.8

TABLE 6.4 STAGED COMBUSTION TESTS FOR COLORADO COAL (SERIES X)

FINAL DATA EVALUATION

ORIGINAL SERIES AND RUN #-S	TOTAL AIR, %	HEAT, KBTU/ FT**3 / HR.	GAS PRE-HEAT DEG F	FLUE GAS INPUT (%)	AIR IN BURNER (%)	NOX PPM	CO PPM	O2 %
X A - 1	103.9	34.35	555	0.0	103.9	568	1700	0.9
X A - 2	116.3	38.43	580	0.0	116.3	917	130	3.2
X A - 3	115.7	38.20	593	0.0	115.7	869	30	3.1
X A - 4	133.2	36.63	606	0.0	133.2	1057	100	5.3
X A - 5	148.3	39.61	620	0.0	148.3	1207	100	6.8
X A - 6	112.3	52.42	610	0.0	112.3	986	325	2.6
X A - 7	113.7	51.95	615	0.0	113.7	990	60	2.8
X A - 8	114.3	50.93	594	0.0	114.3	965	150	2.9
X A - 9	113.0	51.17	597	0.0	113.0	1056	120	2.7
X A - 10	115.0	50.93	598	0.0	115.0	1135	90	3.0
X A - 11	114.3	51.32	619	0.0	114.3	1068	100	2.9
X A - 12	123.8	53.37	630	0.0	123.8	1249	70	4.2
X A - 13	135.1	54.62	641	0.0	135.1	1391	75	5.5
X A - 14	117.7	49.99	623	0.0	117.7	1129	180	3.4
X A - 15	114.3	51.72	603	0.0	114.3	1121	150	2.9
X A - 16	113.7	51.48	622	0.0	113.7	1035	120	2.8
X A - 17	145.1	52.89	607	0.0	145.1	1364	60	6.5
X A - 18	147.2	52.82	587	0.0	147.2	1396	60	6.7
X A - 19	114.3	57.30	630	0.0	114.3	1039	180	2.9
X A - 20	104.8	46.21	596	0.0	104.8	679	1600	1.1
X A - 21	119.2	60.99	638	0.0	119.2	1182	120	3.6
X A - 22	115.0	47.47	286	0.0	115.0	874	130	3.0
X A - 23	144.1	34.42	290	0.0	144.1	897	30	6.4
X A - 24	103.4	43.38	275	0.0	103.4	415	9500	1.2
X B - 25	103.7	33.17	537	0.0	78.4	252	12500	1.4
X B - 26	115.6	37.57	574	0.0	94.3	571	300	3.1
X B - 27	115.0	34.82	583	0.0	67.7	288	1900	3.1
X B - 28	144.0	39.06	606	0.0	117.2	990	100	6.4
X B - 29	139.9	39.30	632	0.0	88.1	582	100	6.0
X B - 30	114.9	51.72	593	0.0	104.4	935	180	3.0
X B - 31	114.9	49.91	594	0.0	93.6	761	150	3.0
X B - 32	111.3	52.50	620	0.0	72.1	398	360	2.4
X B - 33	116.2	47.63	629	0.0	62.4	386	360	3.2
X B - 34	119.7	46.61	639	0.0	54.4	389	510	3.7
X B - 35	119.1	48.96	621	0.0	96.8	784	180	3.6
X B - 36	113.6	47.16	636	0.0	70.6	412	360	2.8
X B - 37	117.7	44.72	629	0.0	58.4	385	210	3.4
X B - 38	112.3	45.27	634	0.0	45.5	329	360	2.6
X B - 39	120.6	48.10	603	0.0	109.6	899	210	3.8
X B - 40	132.3	43.07	585	0.0	107.3	898	30	5.2
X B - 41	126.2	43.93	606	0.0	78.3	651	60	4.5
X B - 42	123.8	44.48	606	0.0	66.5	539	90	4.2
X B - 43	128.7	43.15	611	0.0	56.2	505	150	4.8
X B - 44	120.6	48.89	592	0.0	98.7	748	240	3.8
X B - 45	150.5	48.41	584	0.0	106.2	1039	60	7.0
X B - 46	140.0	52.03	591	0.0	106.4	979	60	6.0
X B - 47	152.8	46.53	606	0.0	70.2	771	60	7.2
X B - 48	105.1	44.41	588	0.0	80.2	331	4400	1.3
X B - 49	104.0	42.36	604	0.0	53.5	312	3100	1.0
X B - 50	117.0	59.73	627	0.0	94.7	763	150	3.3
X B - 51	119.1	56.75	644	0.0	72.5	496	340	3.6
X B - 52	118.8	45.27	276	0.0	87.9	433	1200	3.6
X B - 53	115.9	44.33	279	0.0	58.9	395	1200	3.2
X B - 54	118.8	43.46	281	0.0	89.8	493	1100	3.6
X B - 55	118.8	44.17	279	0.0	63.0	477	1100	3.6
X B - 56	147.2	32.93	283	0.0	88.1	477	150	6.7
X B - 57	104.7	41.89	273	0.0	46.9	255	4000	1.2

TABLE 6.5 SLOT CHANGES FOR COLORADO COAL (SERIES XI)

FINAL DATA EVALUATION

ORIGINAL SERIES AND RUN #-S	TOTAL AIR, %	HEAT, KBTU/ FT**3 / HR.	GAS PRE-HEAT DEG F	FLUE GAS INPUT (%)	AIR IN BURNER (%)	NOX PPM	CO PPM	O2 %
XI A - 1	115.6	49.44	618	0.0	115.6	1108	120	3.1
XI A - 2	114.6	56.59	584	0.0	91.4	885	120	2.9
XI A - 3	117.0	45.74	620	0.0	62.6	414	100	3.3
XI A - 4	113.6	48.02	605	0.0	87.0	745	200	2.8
XI A - 5	114.3	47.55	618	0.0	61.6	551	90	2.9
XI A - 6	102.9	48.65	595	0.0	102.9	757	3700	0.8
XI A - 7	103.9	46.45	593	0.0	75.4	467	3500	1.0
XI A - 8	106.4	43.07	609	0.0	49.6	315	120	1.3
XI A - 9	104.2	40.95	640	0.0	71.9	389	2200	1.0
XI A -10	104.2	44.01	607	0.0	49.3	315	1200	0.9
XI A -11	115.0	36.00	588	0.0	115.0	981	75	3.0
XI A -12	116.3	33.80	587	0.0	81.9	557	60	3.2
XI A -13	115.0	30.26	605	0.0	43.6	288	90	3.0
XI A -14	115.6	32.77	594	0.0	48.8	342	100	3.1
XI B - 1	113.7	51.01	649	0.0	113.7	1083	90	2.8
XI B - 2	115.6	48.49	609	0.0	88.3	834	165	3.1
XI B - 3	114.0	44.96	620	0.0	58.0	414	115	2.8
XI B - 4	112.3	50.77	616	0.0	85.2	704	310	2.6
XI B - 5	115.6	48.10	661	0.0	64.0	574	115	3.1
XI B - 6	104.3	48.02	595	0.0	104.3	796	2700	1.0
XI B - 7	104.0	43.93	594	0.0	76.6	434	2000	0.9
XI B - 8	104.4	41.18	605	0.0	49.9	399	1200	1.0
XI B - 9	102.1	47.31	601	0.0	77.3	401	8000	0.8
XI B -10	104.0	45.35	606	0.0	55.9	319	3200	1.0
XI B -11	114.0	36.31	591	0.0	114.0	857	165	2.8
XI B -12	114.3	33.56	592	0.0	84.5	601	140	2.9
XI B -13	116.3	31.91	590	0.0	57.4	434	150	3.2
XI B -14	116.3	31.83	580	0.0	57.3	360	190	3.2
XI C - 1	116.3	51.32	616	0.0	116.3	1096	150	3.2
XI C - 2	114.2	48.65	598	0.0	87.1	673	430	2.9
XI C - 3	114.1	46.45	628	0.0	60.2	295	810	2.9
XI C - 4	115.9	48.18	604	0.0	88.0	611	1200	3.2
XI C - 5	114.9	47.31	630	0.0	62.5	513	300	3.0
XI C - 6	103.8	49.59	605	0.0	103.8	784	4000	1.0
XI C - 7	103.7	46.29	608	0.0	75.7	338	6500	1.1
XI C - 8	104.3	44.56	615	0.0	49.5	199	4000	1.1
XI C - 9	100.8	43.23	603	0.0	70.7	385	9500	0.6
XI C -10	101.1	45.82	623	0.0	47.7	226	9500	0.7
XI C -11	113.6	37.02	595	0.0	113.6	940	125	2.8
XI C -12	114.7	33.56	593	0.0	79.2	356	960	3.0
XI C -13	113.5	32.62	613	0.0	48.1	250	500	2.8
XI C -14	114.3	33.87	610	0.0	49.1	364	260	2.9

TABLE 6.6 BURNER CHANGES FOR COLORADO COAL (SERIES XII)

FINAL DATA EVALUATION

ORIGINAL SERIES AND RUN #-S	TOTAL AIR, %	HEAT, KBTU/ FT**3 / HR.	GAS PRE-HEAT DEG F	FLUE GAS INPUT (%)	AIR IN BURNER (%)	NOX PPM	CO PPM	O2 %
XII A- 1	116.3	49.83	620	0.0	116.3	1191	100	3.2
XII A- 2	117.7	48.89	623	0.0	88.9	933	75	3.4
XII A- 3	117.0	46.45	630	0.0	63.1	512	60	3.3
XII A- 4	114.6	38.59	598	0.0	79.5	720	75	2.9
XII A- 5	115.6	48.81	629	0.0	63.8	567	150	3.1
XII A- 6	104.0	48.81	603	0.0	104.0	824	3200	1.0
XII A- 7	105.6	47.39	607	0.0	79.4	538	1200	1.3
XII A- 8	105.5	45.51	617	0.0	56.6	278	1600	1.3
XII A- 9	104.1	48.26	606	0.0	79.1	434	2600	1.0
XII A-10	105.6	47.71	616	0.0	58.1	363	2100	1.3
XII A-11	153.8	55.65	650	0.0	153.8	1327	180	7.3
XII A-12	116.3	50.22	620	0.0	116.3	1037	200	3.2
XII A-13	113.7	37.02	590	0.0	113.7	892	90	2.8
XII A-14	115.0	33.48	579	0.0	80.2	506	80	3.0
XII A-15	118.4	31.36	605	0.0	48.0	341	75	3.5
XII A-16	117.7	33.87	581	0.0	81.6	540	60	3.4
XII A-17	114.3	33.80	609	0.0	49.5	332	150	2.9
XII A-18	115.0	46.53	301	0.0	115.0	1002	100	3.0
XII A-19	155.1	47.79	313	0.0	155.1	1192	60	7.4
XII A-20	104.5	44.33	296	0.0	104.5	745	2000	1.0
XII B- 1	114.6	51.01	620	0.0	114.6	1220	65	2.9
XII B- 2	112.9	49.12	611	0.0	86.3	914	330	2.7
XII B- 3	113.9	46.76	625	0.0	60.3	420	300	2.8
XII B- 4	113.3	48.18	598	0.0	86.2	865	60	2.8
XII B- 5	114.0	47.00	623	0.0	61.4	566	100	2.8
XII B- 6	103.7	45.58	587	0.0	103.7	871	2400	0.9
XII B- 7	104.4	44.88	601	0.0	76.9	576	4300	1.1
XII B- 8	104.4	42.28	603	0.0	51.2	303	1400	1.0
XII B- 9	102.0	48.34	597	0.0	77.1	524	3600	0.6
XII B-10	104.7	45.03	611	0.0	53.7	304	2150	1.1
XII B-11	155.0	53.44	642	0.0	155.0	1401	120	7.4
XII B-12	114.0	50.69	618	0.0	114.0	1216	100	2.8
XII B-13	113.6	36.63	589	0.0	113.6	1022	200	2.8
XII B-14	113.0	35.13	593	0.0	79.0	631	140	2.7
XII B-15	114.3	32.22	609	0.0	44.8	357	75	2.9
XII B-16	115.0	34.66	594	0.0	80.5	607	55	3.0
XII B-17	115.6	34.58	600	0.0	52.7	383	115	3.1
XII B-18	113.5	47.94	289	0.0	113.5	1046	450	2.8
XII B-19	150.5	47.94	288	0.0	150.5	1183	30	7.0
XII B-20	102.9	45.11	280	0.0	102.9	748	3900	0.8
XII C- 1	114.0	51.32	628	0.0	114.0	1108	60	2.8
XII C- 2	112.6	48.34	616	0.0	85.4	875	330	2.6
XII C- 3	115.0	45.11	637	0.0	60.2	426	100	3.0
XII C- 4	113.7	47.86	628	0.0	86.4	726	120	2.8
XII C- 5	113.9	46.92	635	0.0	61.1	489	300	2.8
XII C- 6	101.8	46.06	600	0.0	101.8	726	4400	0.6
XII C- 7	102.1	42.76	594	0.0	72.9	408	5000	0.7
XII C- 8	104.5	40.48	609	0.0	44.7	326	1000	1.0
XII C- 9	102.8	45.11	598	0.0	74.2	420	3950	0.8
XII C-10	105.5	42.99	609	0.0	48.0	238	2800	1.3
XII C-11	145.0	51.24	639	0.0	145.0	1395	200	6.5
XII C-12	112.4	51.56	614	0.0	112.4	1172	200	2.6
XII C-13	112.1	37.18	583	0.0	112.1	1048	100	2.5
XII C-14	111.5	47.00	605	0.0	86.4	549	500	2.4
XII C-15	113.0	34.03	596	0.0	49.3	351	155	2.7
XII C-16	111.5	36.86	584	0.0	79.0	569	240	2.4
XII C-17	111.7	34.50	605	0.0	47.1	287	330	2.5
XII C-18	114.2	47.24	294	0.0	114.2	1062	500	2.9
XII C-19	148.3	50.30	302	0.0	148.3	1165	180	6.8
XII C-20	103.1	45.19	285	0.0	103.1	714	3700	0.8

In addition, Tables 6.7 to 6.14 inclusive are the final calculations based on the data from Tables 6.1 to 6.6 for use in evaluation of the NO reduction for flue gas recirculation and/or staged combustion. Each of the series is described by two tables; part 1 and part 2. The tabular headings are described as:

Part 1

1) Original Test Numbers: When coupled with the Series Number in the table title, this is self-explanatory.

2) Averages for Tests: These values are the average values for the two tests for:

   a) Load, %: The percentage of fuel Btu input based on 5,000,000 Btu/hr.

   b) Excess Air, %: The percent of air based on stoichiometric air added over and above the 100% theoretical air level.

   c) Temperature, ^{o}F: The total preheat for the fuel/air input.

3) Burner air, %: The percentage of 100% theoretical (stoichiometric) air coming through the burner as first stage air.

4) Side or Front Slots: The slot position used for second stage air if the tests involved staged combustion.

5) Flue Gas Recycled, %: The percentage of

flue gas recycled from the stack into the combustion air.

6) Burner or Ports: Not applicable to Phase II.

Part 2 7) NO (ppm): The NO measurements in the flue gas corrected to dry, 3% oxygen conditions for the following tests:

a) Base Value: The test before any NO reduction methods were used.

b) With Changes: The test made with NO reduction methods(s) applied.

c) Reduction: The difference between columns a and b.

8) Reduction in NO, %: The percentage reduction from columns 7a and 7b based on the initial value in 7a.

TABLE 6.7 SUMMARY OF SERIES IX, PART 1

FINAL REDUCTIONS (PART 1)

ORIGINAL TEST NOS.	AVERAGES FOR TESTS			BURNER AIR, %	SIDE OR FRONT SLOTS	FLUE GAS RECYC. %	BURNER OR PORTS
	LOAD, %	EXCESS AIR, %	TEMP. DEG F				
IX - 1/3	119.8	12.1	616	112.1	----	6.6	BURNER
IX - 1/4	119.3	11.4	615	111.4	----	18.5	BURNER
IX - 2/5	85.0	14.7	587	114.7	----	22.7	BURNER

TABLE 6.8 SUMMARY OF SERIES IX, PART 2

FINAL REDUCTIONS (PART 2)

ORIGINAL TEST NOS.	NO (PPM)			REDUCTION IN NO, %
	BASE VALUE	WITH CHANGES	REDUCTION	
IX - 1/3	1018 ± 12	968 ± 11	50 ± 16	4.9 ± 1.6
IX - 1/4	1018 ± 12	888 ± 28	130 ± 30	12.9 ± 3.0
IX - 2/5	811 ± 7	770 ± 11	41 ± 13	5.1 ± 1.6

TABLE 6.9 SUMMARY OF SERIES X, PART 1

FINAL REDUCTIONS (PART 1)

ORIGINAL TEST NOS.	AVERAGES FOR TESTS: LOAD, %	AVERAGES FOR TESTS: EXCESS AIR, %	AVERAGES FOR TESTS: TEMP. DEG F	BURNER AIR, %	SIDE OR FRONT SLOTS	FLUE GAS RECYC. %	BURNER OR PORTS
X - 1/25	75.7	3.8	546	78.4	FRONT	0.0	----
X - 2/26	88.1	15.9	577	94.3	FRONT	0.0	----
X - 3/27	86.1	15.3	568	67.7	FRONT	0.0	----
X - 5/28	88.3	46.1	613	117.2	FRONT	0.0	----
X - 5/29	89.9	44.1	626	88.1	FRONT	0.0	----
X -15/30	118.3	14.6	598	104.4	FRONT	0.0	----
X -10/31	116.4	14.9	596	93.6	FRONT	0.0	----
X -19/32	127.5	12.8	625	72.1	FRONT	0.0	----
X -10/33	115.9	15.6	613	62.4	FRONT	0.0	----
X -14/34	113.7	18.7	631	54.4	FRONT	0.0	----
X -14/35	113.2	18.4	622	96.8	FRONT	0.0	----
X -11/36	114.4	13.9	627	70.6	FRONT	0.0	----
X -14/37	111.1	17.7	626	58.4	FRONT	0.0	----
X -11/38	114.2	13.3	626	45.5	FRONT	0.0	----
X -14/39	111.6	19.1	613	109.6	SIDE	0.0	----
X -13/40	110.1	33.7	613	107.3	SIDE	0.0	----
X -12/41	112.1	25.0	618	78.3	SIDE	0.0	----
X -12/42	113.5	23.8	618	66.5	SIDE	0.0	----
X -13/43	113.3	31.9	626	56.2	SIDE	0.0	----
X -14/44	113.0	19.1	607	98.7	SIDE	0.0	----
X -18/45	114.8	48.8	585	106.2	FRONT	0.0	----
X -13/46	120.4	37.5	616	106.4	SIDE	0.0	----
X -18/47	114.9	50.0	596	70.2	SIDE	0.0	----
X -20/48	105.9	4.9	592	80.2	FRONT	0.0	----
X -20/49	105.4	4.4	600	53.5	FRONT	0.0	----
X -21/50	137.7	18.1	632	94.7	FRONT	0.0	----
X -21/51	136.1	19.1	641	72.5	FRONT	0.0	----
X -22/52	113.7	16.9	281	87.9	FRONT	0.0	----
X -22/53	113.3	15.4	282	58.9	FRONT	0.0	----
X -22/54	111.5	16.9	283	89.8	SIDE	0.0	----
X -22/55	113.0	16.9	282	63.0	SIDE	0.0	----
X -23/56	82.4	45.6	286	88.1	FRONT	0.0	----
X -24/57	105.9	4.0	274	46.9	FRONT	0.0	----

TABLE 6.10 SUMMARY OF SERIES X, PART 2

FINAL REDUCTIONS (PART 2)

ORIGINAL TEST NOS.	NO (PPM): BASE VALUE	NO (PPM): WITH CHANGES	NO (PPM): REDUCTION	REDUCTION IN NO, %
X - 1/25	568 ± 9	252 ± 5	316 ± 10	55.6 ± 2.0
X - 2/26	917 ± 37	571 ± 6	346 ± 37	37.7 ± 4.4
X - 3/27	869 ± 26	288 ± 1	581 ± 26	66.9 ± 3.6
X - 5/28	1207 ± 64	990 ± 22	217 ± 68	18.0 ± 5.7
X - 5/29	1207 ± 64	582 ± 3	625 ± 64	51.8 ± 6.0
X -15/30	1121 ± 34	935 ± 40	186 ± 52	16.6 ± 4.7
X -10/31	1135 ± 9	761 ± 36	374 ± 37	33.0 ± 3.3
X -19/32	1038 ± 16	398 ± 12	640 ± 20	61.7 ± 2.1
X -10/33	1135 ± 9	386 ± 2	749 ± 9	66.0 ± 1.0
X -14/34	1129 ± 16	389 ± 6	740 ± 17	65.5 ± 1.8
X -14/35	1129 ± 16	784 ± 48	345 ± 51	30.6 ± 4.5
X -11/36	1068 ± 23	412 ± 55	656 ± 60	61.4 ± 5.7
X -14/37	1129 ± 16	385 ± 2	744 ± 16	65.9 ± 1.7
X -11/38	1068 ± 23	329 ± 2	739 ± 23	69.2 ± 2.6
X -14/39	1129 ± 16	899 ± 19	230 ± 25	20.4 ± 2.2
X -13/40	1391 ± 73	898 ± 29	493 ± 79	35.4 ± 5.9
X -12/41	1248 ± 40	651 ± 19	597 ± 44	47.8 ± 3.9
X -12/42	1248 ± 40	539 ± 14	709 ± 42	56.8 ± 3.9
X -13/43	1391 ± 73	505 ± 18	886 ± 75	63.7 ± 6.4
X -14/44	1129 ± 16	748 ± 7	381 ± 17	33.7 ± 1.6
X -18/45	1396 ± 11	1039 ± 5	357 ± 12	25.6 ± 0.9
X -13/46	1391 ± 73	979 ± 17	412 ± 75	29.6 ± 5.6
X -18/47	1396 ± 11	771 ± 31	625 ± 33	44.8 ± 2.4
X -20/48	679 ± 10	331 ± 5	348 ± 11	51.3 ± 1.8
X -20/49	679 ± 10	312 ± 2	367 ± 10	54.1 ± 1.7
X -21/50	1182 ± 20	763 ± 7	419 ± 21	35.4 ± 1.9
X -21/51	1182 ± 20	496 ± 10	686 ± 22	58.0 ± 2.1
X -22/52	874 ± 26	433 ± 2	441 ± 26	50.5 ± 3.3
X -22/53	874 ± 26	395 ± 2	479 ± 26	54.8 ± 3.4
X -22/54	874 ± 26	493 ± 9	381 ± 28	43.6 ± 3.4
X -22/55	874 ± 26	477 ± 9	397 ± 28	45.4 ± 3.4
X -23/56	897 ± 4	477 ± 7	420 ± 8	46.8 ± 0.9
X -24/57	415 ± 14	255 ± 18	160 ± 23	38.6 ± 5.6

TABLE 6.11 SUMMARY OF SERIES XI, PART 1

FINAL REDUCTIONS (PART 1)

ORIGINAL TEST NOS.	AVERAGES FOR TESTS			BURNER AIR, %	SIDE OR FRONT SLOTS	FLUE GAS RECYC. %	BURNER OR PORTS
	LOAD, %	EXCESS AIR, %	TEMP. DEG F				
A 1/ 2	120.6	15.1	601	91.4	FRONT	0.0	----
A 1/ 3	111.3	16.3	619	62.6	FRONT	0.0	----
A 1/ 4	112.3	14.6	611	87.0	SIDE	0.0	----
A 1/ 5	113.7	14.9	618	61.6	SIDE	0.0	----
A 6/ 7	111.3	3.4	594	75.4	FRONT	0.0	----
A 6/ 8	109.2	4.6	602	49.6	FRONT	0.0	----
A 6/ 9	104.6	3.5	617	71.9	SIDE	0.0	----
A 6/10	110.4	3.5	601	49.3	SIDE	0.0	----
A 11/12	81.2	15.6	587	81.9	FRONT	0.0	----
A 11/13	79.0	15.0	596	43.6	FRONT	0.0	----
A 11/14	82.0	15.3	591	48.8	SIDE	0.0	----
B 1/ 2	114.3	14.6	629	88.3	FRONT	0.0	----
B 1/ 3	112.3	13.8	634	58.0	FRONT	0.0	----
B 1/ 4	117.1	13.0	632	85.2	SIDE	0.0	----
B 1/ 5	115.3	14.6	655	64.0	SIDE	0.0	----
B 6/ 7	107.6	4.1	594	76.6	FRONT	0.0	----
B 6/ 8	106.3	4.3	600	49.9	FRONT	0.0	----
B 6/ 9	111.5	3.2	598	77.3	SIDE	0.0	----
B 6/10	110.9	4.1	600	55.9	SIDE	0.0	----
B 11/12	81.3	14.1	586	84.5	FRONT	0.0	----
B 11/13	80.9	15.1	590	57.4	FRONT	0.0	----
B 11/14	80.9	15.1	585	57.3	SIDE	0.0	----
C 1/ 2	115.1	15.2	607	87.1	FRONT	0.0	----
C 1/ 3	114.4	15.2	622	60.2	FRONT	0.0	----
C 1/ 4	114.5	16.1	610	88.0	SIDE	0.0	----
C 1/ 5	115.3	15.6	623	62.5	SIDE	0.0	----
C 6/ 7	112.0	3.7	606	75.7	FRONT	0.0	----
C 6/ 8	112.1	4.0	610	49.5	FRONT	0.0	----
C 6/ 9	108.8	2.3	604	70.7	SIDE	0.0	----
C 6/10	113.6	2.4	614	47.7	SIDE	0.0	----
C 11/12	82.4	14.1	594	79.2	FRONT	0.0	----
C 11/13	83.0	13.5	604	48.1	FRONT	0.0	----
C 11/14	84.5	13.9	602	49.1	SIDE	0.0	----

TABLE 6.12 SUMMARY OF SERIES XI, PART 2

FINAL REDUCTIONS (PART 2)

ORIGINAL TEST NOS.	NO (PPM)			REDUCTION IN NO. %
	BASE VALUE	WITH CHANGES	REDUCTION	
A 1/ 2	1108 ± 63	885 ± 29	223 ± 69	20.1 ± 6.4
A 1/ 3	1108 ± 63	414 ± 17	694 ± 65	62.6 ± 6.9
A 1/ 4	1108 ± 63	745 ± 32	363 ± 71	32.8 ± 6.6
A 1/ 5	1108 ± 63	551 ± 20	557 ± 66	50.3 ± 6.6
A 6/ 7	757 ± 20	467 ± 12	290 ± 23	38.3 ± 3.2
A 6/ 8	757 ± 20	315 ± 8	442 ± 22	58.4 ± 3.2
A 6/ 9	757 ± 20	389 ± 13	368 ± 24	48.6 ± 3.4
A 6/10	757 ± 20	315 ± 11	442 ± 23	58.4 ± 3.4
A 11/12	981 ± 48	557 ± 17	424 ± 51	43.2 ± 5.6
A 11/13	981 ± 48	288 ± 6	693 ± 48	70.6 ± 6.0
A 11/14	981 ± 48	342 ± 11	639 ± 49	65.1 ± 5.9
B 1/ 2	1083 ± 30	834 ± 18	249 ± 35	23.0 ± 3.3
B 1/ 3	1083 ± 30	414 ± 13	669 ± 33	61.8 ± 3.5
B 1/ 4	1083 ± 30	704 ± 21	379 ± 37	35.0 ± 3.5
B 1/ 5	1083 ± 30	574 ± 17	509 ± 34	47.0 ± 3.4
B 6/ 7	796 ± 26	434 ± 15	362 ± 30	45.5 ± 4.1
B 6/ 8	796 ± 26	399 ± 8	397 ± 27	49.9 ± 3.8
B 6/ 9	796 ± 26	401 ± 11	395 ± 28	49.6 ± 3.9
B 6/10	796 ± 26	318 ± 5	478 ± 26	60.1 ± 3.9
B 11/12	857 ± 11	601 ± 6	256 ± 13	29.9 ± 1.5
B 11/13	857 ± 11	434 ± 12	423 ± 16	49.4 ± 2.0
B 11/14	857 ± 11	360 ± 9	497 ± 14	58.0 ± 1.8
C 1/ 2	1096 ± 45	673 ± 67	423 ± 81	38.6 ± 7.5
C 1/ 3	1096 ± 45	295 ± 6	801 ± 45	73.1 ± 5.1
C 1/ 4	1096 ± 45	611 ± 17	485 ± 48	44.3 ± 4.8
C 1/ 5	1096 ± 45	513 ± 13	583 ± 47	53.2 ± 4.8
C 6/ 7	784 ± 16	338 ± 8	446 ± 18	56.9 ± 2.6
C 6/ 8	784 ± 16	199 ± 1	585 ± 16	74.6 ± 2.5
C 6/ 9	784 ± 16	385 ± 4	399 ± 16	50.9 ± 2.3
C 6/10	784 ± 16	226 ± 8	558 ± 18	71.2 ± 2.7
C 11/12	940 ± 10	356 ± 2	584 ± 10	62.1 ± 1.3
C 11/13	940 ± 10	250 ± 6	690 ± 12	73.4 ± 1.5
C 11/14	940 ± 10	364 ± 9	576 ± 13	61.3 ± 1.6

TABLE 6.13 SUMMARY OF SERIES XII, PART 1

FINAL REDUCTIONS (PART 1)

ORIGINAL TEST NOS.	AVERAGES FOR TESTS			BURNER AIR, %	SIDE OR FRONT SLOTS	FLUE GAS RECYC. %	BURNER OR PORTS
	LOAD, %	EXCESS AIR, %	TEMP. DEG F				
A 1/ 2	113.9	17.0	621	88.9	FRONT	0.0	----
A 1/ 3	112.9	16.6	625	63.1	FRONT	0.0	----
A 1/ 4	102.4	15.4	609	79.5	SIDE	0.0	----
A 1/ 5	115.6	15.9	624	63.8	SIDE	0.0	----
A 6/ 7	112.3	4.8	605	79.4	FRONT	0.0	----
A 6/ 8	111.7	4.8	610	56.6	FRONT	0.0	----
A 6/ 9	113.3	4.0	604	79.1	SIDE	0.0	----
A 6/10	114.3	4.8	609	58.1	SIDE	0.0	----
A 13/14	82.4	14.3	584	80.2	FRONT	0.0	----
A 13/15	81.5	16.0	597	48.0	FRONT	0.0	----
A 13/16	82.8	15.7	585	81.6	SIDE	0.0	----
A 13/17	84.4	14.0	599	49.5	SIDE	0.0	----
B 1/ 2	115.5	13.7	615	86.3	FRONT	0.0	----
B 1/ 3	114.6	14.2	622	60.3	FRONT	0.0	----
B 1/ 4	114.4	13.9	609	86.2	SIDE	0.0	----
B 1/ 5	114.9	14.3	621	61.4	SIDE	0.0	----
B 6/ 7	105.9	4.0	594	76.9	FRONT	0.0	----
B 6/ 8	104.9	4.0	595	51.2	FRONT	0.0	----
B 6/ 9	110.1	2.8	592	77.1	SIDE	0.0	----
B 6/10	108.0	4.2	599	53.7	SIDE	0.0	----
B 13/14	83.8	13.3	591	79.0	FRONT	0.0	----
B 13/15	82.2	13.9	599	44.8	FRONT	0.0	----
B 13/16	83.1	14.3	591	80.5	SIDE	0.0	----
B 13/17	84.8	14.6	594	52.7	SIDE	0.0	----
C 1/ 2	114.8	13.3	622	85.4	FRONT	0.0	----
C 1/ 3	112.9	14.5	632	60.2	FRONT	0.0	----
C 1/ 4	114.1	13.8	628	86.4	SIDE	0.0	----
C 1/ 5	115.0	13.9	631	61.1	SIDE	0.0	----
C 6/ 7	104.3	1.9	597	72.9	FRONT	0.0	----
C 6/ 8	103.5	3.1	604	44.7	FRONT	0.0	----
C 6/ 9	106.9	2.3	599	74.2	SIDE	0.0	----
C 6/10	106.4	3.6	604	48.0	SIDE	0.0	----
C 13/14	98.0	11.8	594	86.4	FRONT	0.0	----
C 13/15	85.0	12.5	589	49.3	FRONT	0.0	----
C 13/16	86.6	11.8	583	79.0	SIDE	0.0	----
C 13/17	85.6	11.9	594	47.1	SIDE	0.0	----

TABLE 6.14 SUMMARY OF SERIES XII, PART 2

FINAL REDUCTIONS (PART 2)

ORIGINAL TEST NOS.	NO (PPM) BASE VALUE	NO (PPM) WITH CHANGES	NO (PPM) REDUCTION	REDUCTION IN NO. %
A 1/ 2	1191 ± 13	933 ± 8	258 ± 15	21.7 ± 1.3
A 1/ 3	1191 ± 13	512 ± 21	679 ± 25	57.0 ± 2.2
A 1/ 4	1191 ± 13	720 ± 23	471 ± 26	39.5 ± 2.3
A 1/ 5	1191 ± 13	567 ± 21	624 ± 25	52.4 ± 2.2
A 6/ 7	824 ± 23	538 ± 22	286 ± 30	34.7 ± 3.7
A 6/ 8	824 ± 23	278 ± 8	546 ± 22	66.3 ± 3.1
A 6/ 9	824 ± 23	434 ± 15	390 ± 25	47.3 ± 3.2
A 6/10	824 ± 23	363 ± 15	461 ± 25	55.9 ± 3.3
A 13/14	892 ± 29	506 ± 24	386 ± 38	43.3 ± 4.4
A 13/15	892 ± 29	341 ± 13	551 ± 32	61.8 ± 4.1
A 13/16	892 ± 29	540 ± 14	352 ± 32	39.5 ± 3.8
A 13/17	892 ± 29	332 ± 13	560 ± 32	62.9 ± 4.1
B 1/ 2	1220 ± 34	914 ± 18	306 ± 38	25.1 ± 3.2
B 1/ 3	1220 ± 34	420 ± 8	800 ± 35	65.6 ± 3.4
B 1/ 4	1220 ± 34	865 ± 15	355 ± 37	29.1 ± 3.2
B 1/ 5	1220 ± 34	566 ± 17	654 ± 38	53.6 ± 3.5
B 6/ 7	871 ± 14	576 ± 16	295 ± 21	33.9 ± 2.5
B 6/ 8	871 ± 14	303 ± 7	568 ± 16	65.2 ± 2.1
B 6/ 9	871 ± 14	524 ± 6	347 ± 15	39.8 ± 1.9
B 6/10	871 ± 14	304 ± 7	567 ± 16	65.1 ± 2.1
B 13/14	1022 ± 15	631 ± 10	391 ± 18	38.3 ± 1.9
B 13/15	1022 ± 15	357 ± 2	665 ± 15	65.1 ± 1.8
B 13/16	1022 ± 15	607 ± 3	415 ± 15	40.6 ± 1.6
B 13/17	1022 ± 15	383 ± 14	639 ± 21	62.5 ± 2.2
C 1/ 2	1108 ± 12	875 ± 8	233 ± 14	21.0 ± 1.3
C 1/ 3	1108 ± 12	426 ± 3	682 ± 12	61.6 ± 1.3
C 1/ 4	1108 ± 12	726 ± 16	382 ± 20	34.5 ± 1.8
C 1/ 5	1108 ± 12	489 ± 13	619 ± 18	55.9 ± 1.7
C 6/ 7	726 ± 0	408 ± 2	318 ± 2	43.8 ± 0.3
C 6/ 8	726 ± 0	326 ± 0	400 ± 0	55.1 ± 0.0
C 6/ 9	726 ± 0	420 ± 8	306 ± 8	42.1 ± 1.1
C 6/10	726 ± 0	238 ± 0	488 ± 0	67.2 ± 0.0
C 13/14	1048 ± 22	549 ± 3	499 ± 22	47.6 ± 2.3
C 13/15	1048 ± 22	351 ± 2	697 ± 22	66.5 ± 2.5
C 13/16	1048 ± 22	569 ± 3	479 ± 22	45.7 ± 2.3
C 13/17	1048 ± 22	287 ± 4	761 ± 22	72.6 ± 2.6

TABLE 6.15 CARBON LOSS AND BURNER EFFICIENCY

SERIES AND TEST NUMBER	FIRING DATA			WEIGHTS, LB./HR.		ASH IN F.G. %	C IN ASH, %	BURNER EFFIC. IN % BY WT.
	AIR %	FLUE HEAT	DEG F	FUEL (DRY)	FLUE GAS			
VII - 1	113	49.59	608	428 *****	5684	0.39	29.0	98.6
VII - 3	102	49.96	599	427	5133	0.36	43.2	98.1
VII - 5	142	29.08	570	244	4062	0.40	3.8	99.7
VII - 10	77	45.66	542	413 (SUB)	3783	0.90	50.2	96.3
VII - 11	73	45.55	537	414 (SUB)	3594	0.95	52.1	96.2
VII - 15	104	56.90	602	496	6015	0.82	??	??
VIII- 1	115	52.97	610	454	5911	0.45	13.3	99.2
VIII- 11	117	61.78	620	530	7059	0.45	3.3	99.8
VIII- 14	103	44.01	270	410	4958	0.55	31.5	97.6
X - 5	148	39.61	620	329	5467	0.29	19.1	99.2
X - 6	112	52.42	610	453	5825	0.78	26.1	97.4
X - 22	115	47.47	286	439	5851	0.69	15.6	98.6
X - 26	116	37.57	574	334 (S)	4376	0.61	??	??
X - 32	111	52.50	620	477 (S)	6064	0.91	39.0	95.5
X - 40	132	43.07	585	379 (S)	5710	0.59	20.9	98.1
X - 42	124	44.48	606	410 (S)	5814	0.54	17.9	98.6
X - 43	129	43.15	611	404 (S)	5913	0.51	25.3	98.1
X - 45	151	48.41	584	428 (S)	7214	0.45	9.1	99.3
X - 47	153	46.53	606	429 (S)	7386	0.44	8.2	99.4
X - 48	105	44.41	588	401 (S)	4958	1.03	35.1	95.5
X - 53	116	44.33	279	421 (S)	5590	0.99	33.4	95.6
X - 55	119	44.17	279	419 (S)	5690	0.83	29.0	96.7

***** - (SUB) INDICATES SUBSTOICHIOMETRIC
- (S) INDICATES STAGED COMBUSTION

Table 6.15 is the table showing burner efficiency calculated from combustibles (mostly sclid carbon found in ash samples) from a wide sampling of coal tests. The tabular headings are:

1) Test and Series Number — Self explanatory.

2) Firing Data — The fuel/air input data:

   a) Air, % — The percent of 100% theoretical air.

   b) Flue Heat — Net heat release rate in the furnace in kBtu/ft^3/hr.

   c) Deg F — The total air preheat in ^{o}F.

3) Weights, lb/hr — For dry fuel (coal only) and total flue gas weight.

4) Ash in F.G., % – The total weight percent of solid ash in the flue gas.

5) C in Ash, % – The total weight percent of carbon in the solid ash.

6) Burner Efficiency in Percent by Weight – The amount of coal burned to total flue gas after correction due to unburned solid (and gaseous for all except substoichiometric tests) combustibles.

TABLE 6.16 SLOT CHANGES – STAGED COMBUSTION

STAGED COMBUSTION TESTS: PERCENT REDUCTION IN NO

	"A"	"B"	"C"
Test No.*	No Change	First Change	Second Change
1/2 (F)	20 ± 6	23 ± 3	39 ± 8
1/3 (F)	63 ± 7	62 ± 4	73 ± 5
1/4 (S)	33 ± 7	35 ± 4	44 ± 5
1/5 (S)	50 ± 7	47 ± 3	53 ± 5
6/7 (F)	38 ± 3	46 ± 4	57 ± 3
6/8 (F)	58 ± 3	50 ± 4	75 ± 3
6/9 (S)	49 ± 3	50 ± 4	51 + 2
6/10 (S)	58 ± 3	60 ± 4	71 ± 3
11/12 (F)	43 ± 6	30 ± 2	62 ± 1
11/13 (F)	71 ± 6	49 ± 2	73 ± 2
11/14 (S)	65 ± 6	58 ± 2	61 ± 2

*F indicates front slots for staging; S indicates side slots

Tables 6.16 tabularizes in a simple form the differences in No emission levels for each of the changes in the slots. The column headings in the table represent:

1) "A", No Change (–these are the base line tests):
front slot air entered parallel to the burner
side slot air entered perpendicular to the burner
axis on a 26-inch diameter circle

2) "B", First change:
front slot air entered at a 30 degree inward angle
side slot air entered perpendicular to the burner axis on a 13-inch diameter circle with a 50% increase in slot area opening

3) "C", Second Change:
front slot air entered at a 30 degree outward angle
side slot air entered perpendicular to the burner axis on a 13-inch diameter circle with a 100% increase (over "A") in slot area opening

Tables 6.17 and 6.18 tabularize in the same way as Table 6.16 the differences in NO emission levels for each of the changes in the burner. The column headings in these tables represent:

1) "A", No change — the original burner opening with no cone inserted (These are the base line tests)

2) "B", First change — insertion of a cone into the burner inlet to reduce the effective throat area by 25% and therefore increasing the burner velocity by 33%.

3) "C", Second change — insertion of another cone into the burner inlet to reduce the effective throat area by 50% and thereby increasing the burner velocity by 100%.

B. Colorado Coal Results

All of the figures which follow are the final results of the trends determined in Phase II for the Colorado coal tests. No other fuel was studied in Phase II.

TABLE 6.17 BURNER CHANGES – EXCESS AIR

EXCESS AIR TESTS: PPM NO

Test No.*	"A" No Change	"B" First Change	"C" Second Change
1 (15%)	1191 ± 13	1220 ± 34	1108 ± 12
6 (<5%)	824 ± 20	871 ± 14	726 ± 0
11 (35%)	1327 ± 13	1401 ± 58	1395 ± 29
12 (15%)	1037 ± 27	1216 ± 38	1172 ± 27
13 (15%)**	892 ± 29	1022 ± 15	1048 ± 22
18 (15%)***	1002 ± 35	1046 ± 8	1062 ± 20
19 (35%)***	1192 ± 46	1183 ± 24	1165 ± 5
20 (<5%)***	745 ± 10	746 ± 12	714 ± 12

*Number in parenthesis is excess air level.

**Low load.

***Low preheat.

TABLE 6.18 BURNER CHANGES – STAGED COMBUSTION

STAGED COMBUSTION TESTS: PERCENT REDUCTION OF NO

Test No.*	"A" No Change	"B" First Change	"C" Second Change
1/2 (F)	22 ± 1	25 ± 3	21 ± 1
1/3 (F)	57 ± 2	66 ± 3	62 ± 1
1/4 (S)	40 ± 2	29 ± 3	35 ± 2
1/5 (S)	52 ± 2	54 ± 4	56 ± 2
6/7 (F)	35 ± 4	34 ± 3	44 ± 0
6/8 (F)	66 ± 3	65 ± 2	55 ± 0
6/9 (S)	47 ± 3	46 ± 2	42 ± 1
6/10 (S)	56 ± 3	65 ± 2	67 ± 0
13/14 (F)	43 ± 4	38 ± 2	48 ± 2
13/15 (F)	62 ± 4	65 ± 2	67 ± 3
13/16 (S)	40 ± 4	41 ± 2	46 ± 2
13/17 (S)	63 ± 4	63 ± 2	75 ± 3

*F indicates front slots used for staging; S indicates side slots

Figures 6.1 to 6.3 illustrate the typical major effects observed for the Colorado coal. The variables observed are excess air, firing intensity, and preheat. For these figures, two of the three variables were held constant, and the third is shown on the abscissa. The constant conditions observed in these figures are:

Excess air level – about 15%
Preheat level – about 600°F
Firing intensity – about 40,000 Btu/ft^3/hr.

The important trends observed were:

Excess air – rapid increase in NO emission level peaking at about 30 to 35% excess air
Firing intensity (load or rate of heat release) – increasing NO with increasing load with no apparent leveling or turnover
Preheat – a slight increasing trend of about 35 ppm per 100°F

Figures 6.4 to 6.6 show a comparison of a fine and coarse pulverization* of the Colorado coal for these same three variables. The fine pulverization is ∿90% through a 200 mesh screen and the coarse pulverization is ∿70% through 200 mesh. Fineness is not a major variable in our coal fired test unit. (Ordinarily, for all tests other than fineness, the 70%/-200 mesh pulverization is used for the Colorado coal tests.)

Figure 6.7 illustrates the effect of secondary flue gas recirculation. The flue gas was added to the windbox so that there was thorough mixing of the flue gas and secondary air stream. Very little reduction of NO emission levels was seen for FGR with the Colorado coal.

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*See Appendix A for the sieving analyses for the Colorado coal.

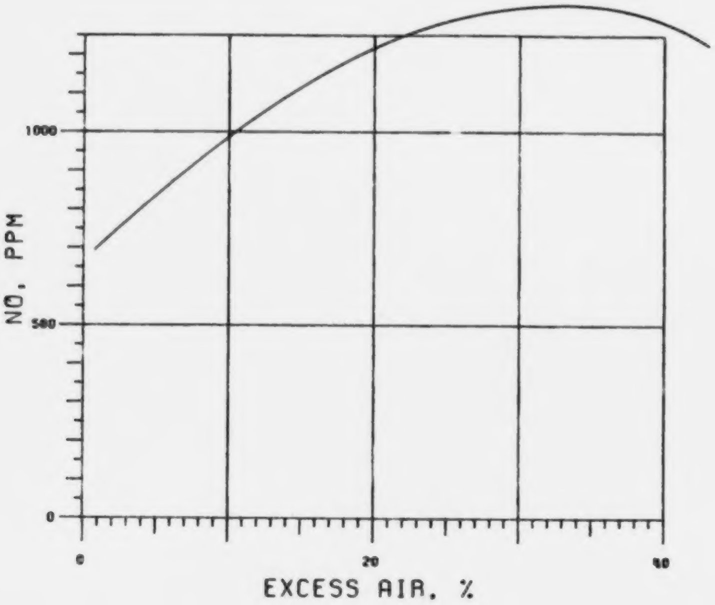

FIGURE 6.1 COLORADO COAL

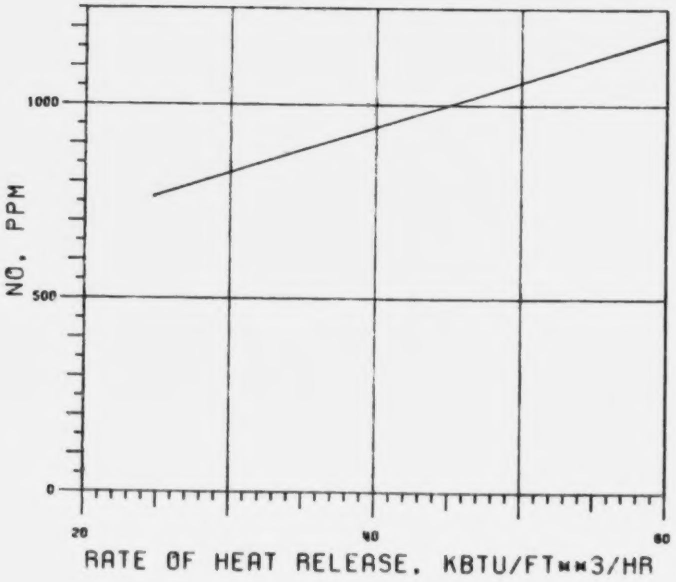

FIGURE 6.2 COLORADO COAL

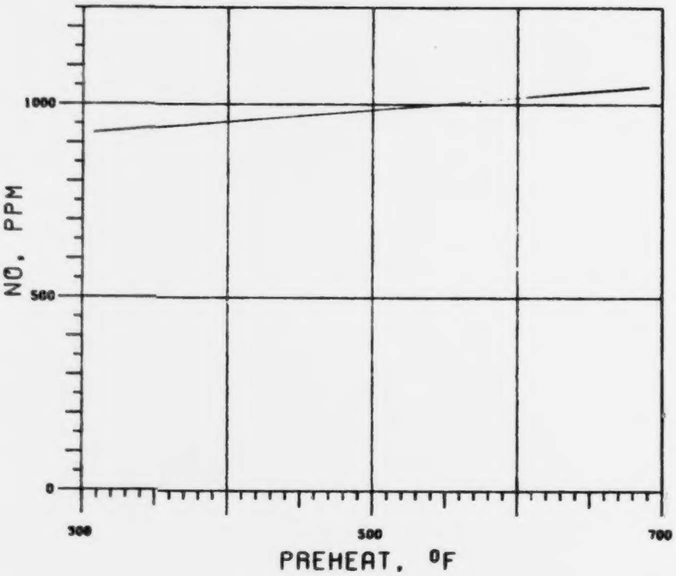

FIGURE 6.3 COLORADO COAL

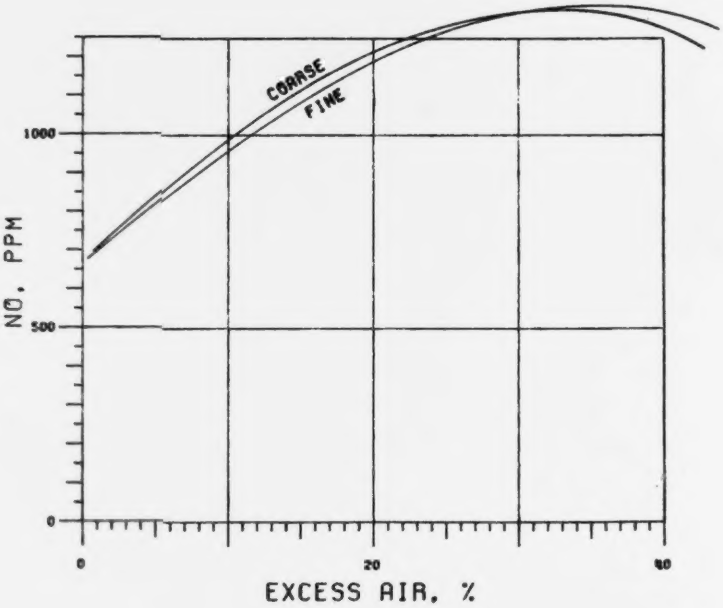

FIGURE 6.4 COLORADO COAL – FINENESS

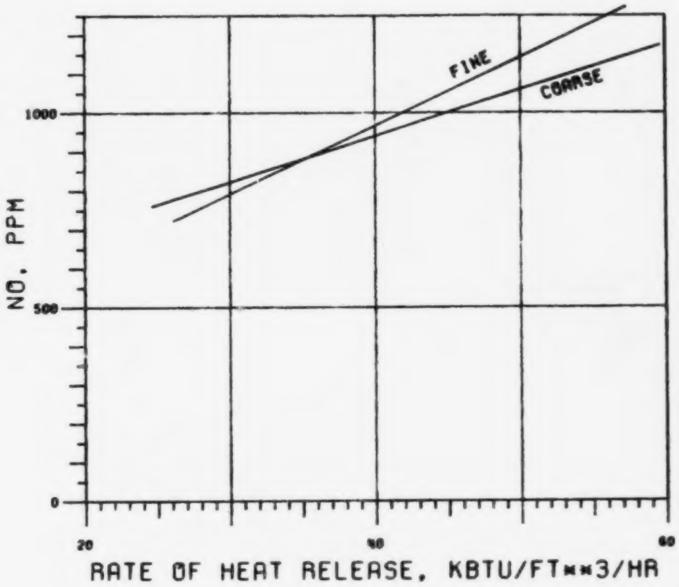

FIGURE 6.5 COLORADO COAL – FINENESS

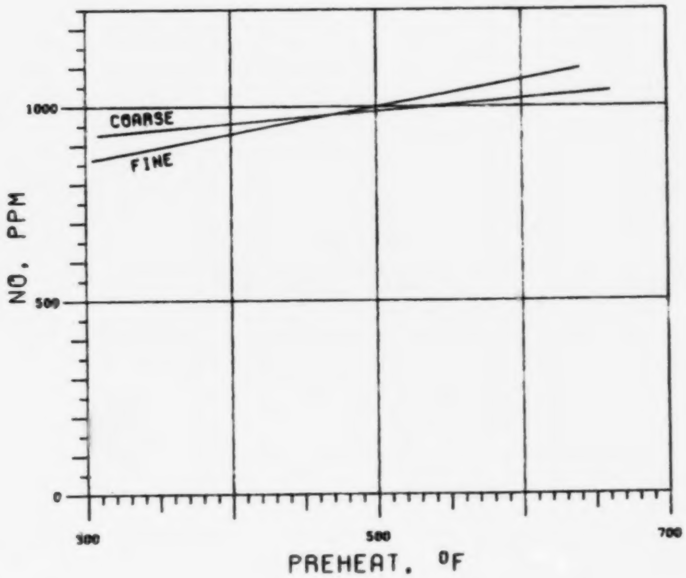

FIGURE 6.6 COLORADO COAL – FINENESS

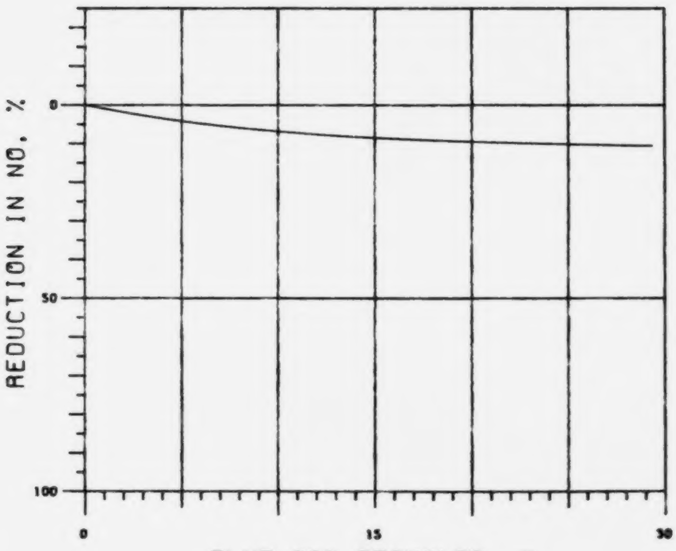

FIGURE 6.7 FLUE GAS RECIRCULATION

Second stage combustion air can be added to our furnace in two ways (see Figure 6.8). The front slots produce a "progressive mixing" and involve addition of the air in the burner area. The side slots, however, produce a defined second stage addition downstream of the burner area. When using the side slots for Colorado coal combustion, incomplete combustion occurred in the center core of the flame at low burner air to total combustion air ratios.

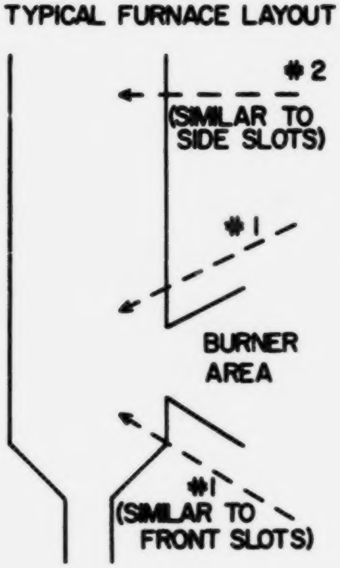

FIGURE 6.8 STAGED COMBUSTION OPTIONS

Figure 6.9 shows the normal (front slot) staged combustion with a total excess air of 15%. The substoichiometric curve was generated by simply shutting off the second stage air. Two important points to be noted in these curves are:

1) The maximum reduction of NO emission level for normal, staged combustion is about 65%.

2) The substoichiometric curve shows no NO emission below about 60% of stoichiometric air.

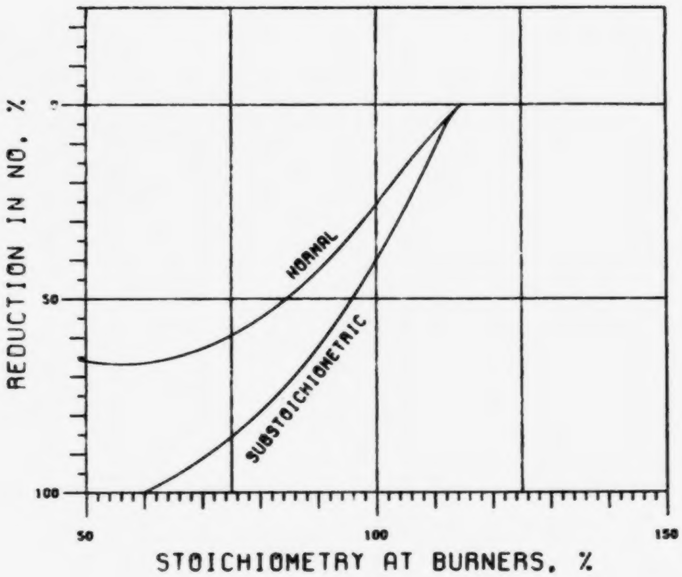

FIGURE 6.9 STAGED – 15% EXCESS AIR

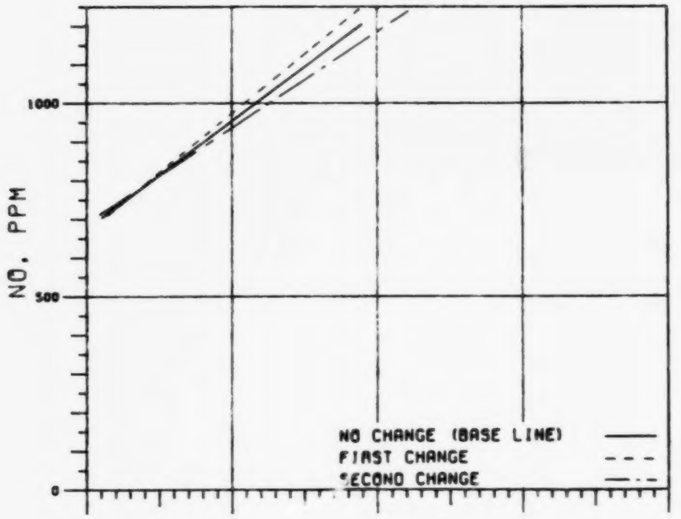

FIGURE 6.10 SLOT CHANGES

Figure 6.10 is a curve showing excess air (a variable which should be unaffected by the slot changes) and giving an idea of the nonreproducible day-to-day fluctuations that were seen, especially at higher excess air levels.

Two changes in the second stage air addition were made to determine the effect of mixing. The front slots were changed to add either the second stage air earlier or later to the first stage combustion. The side slots were changed to lower the mixing velocity of the air. Figure 6.11 represents the effect of these changes:

	Change in:	
	Front Slots	Side Slots
No change: baseline	air parallel to burner	air perpendicular to burner axis on 26-inch diameter circle
First change	air angled inward at 30 degrees	air perpendicular to burner axis on 13-inch diameter circle, slot area increased 50%
Second change	air angled outward at 30 degrees	air perpendicular to burner axis on 13-inch diameter circle, slot area increase 100%

The first change in slot geometry and size did not affect the NO reduction. The second change did have some effect — the change in side slots and in front slots had the same effect. The difference in NO reduction is not large.

Additionally, to compensate for differences in air velocity when excess air was varied or staging occurred, the burner cross section was modified twice to approximate constant velocity conditions. Figures 6.12 to 6.15 show the effects of these changes:

- No change or base line is 100% burner cross sectional area or no change in burner velocity

- First change is a reduction of the burner area by 25% and an increase in burner velocity of 33%

- Second change is a reduction of the burner area by 50% and an increase in burner velocity of 100%.

The changes in burner velocity produced a minimum or no change in the NO emission levels. The variation in day-to-day testing and experimental variations observed in the NO emission levels were of the same order of magnitude of any changes in NO emission due to the burner velocity changes. As a result no significant changes in NO emission levels were evident for changes in burner velocity. (See Figures D.43 to D.48 in Appendix D.)

Figures 6.16 and 6.17 illustrate the effect of load and stoichiometry on the burner efficiency and carbon loss. These figures indicate an interdependence of load and stoichiometry on carbon loss and burner efficiency.

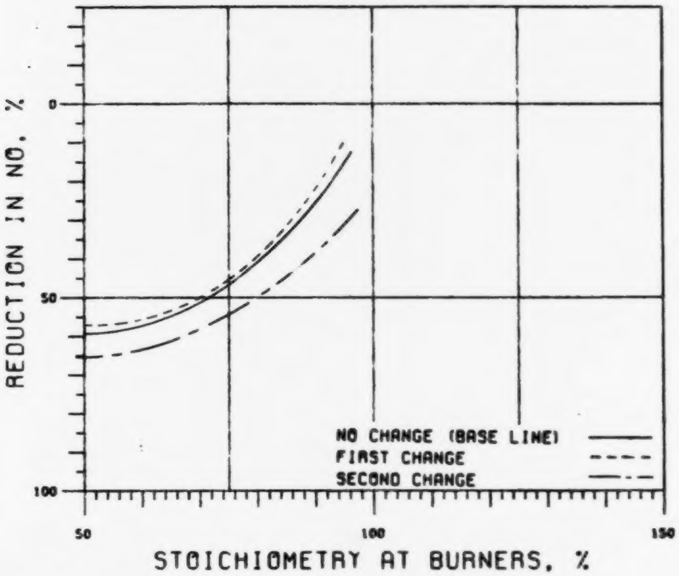

FIGURE 6.11 SLOT CHANGES – 15% AIR

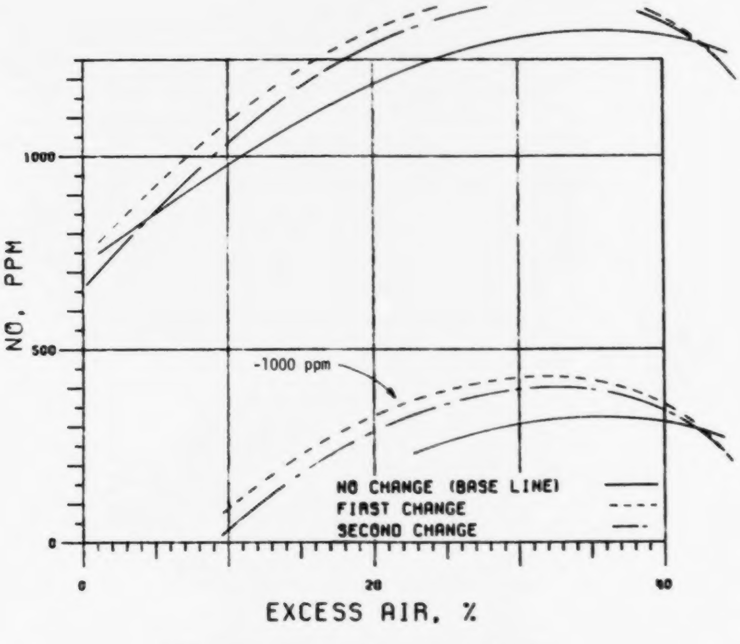

FIGURE 6.12 BURNER CHANGES

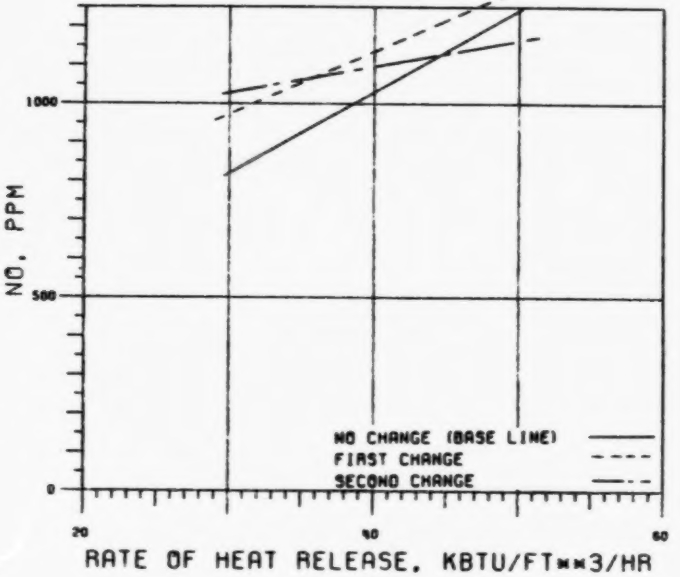

FIGURE 6.13 BURNER CHANGES

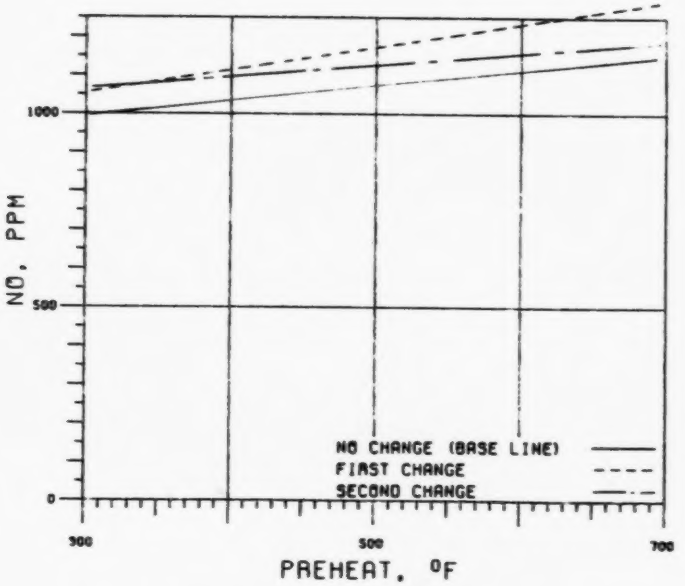

FIGURE 6.14 BURNER CHANGES – 15% AIR

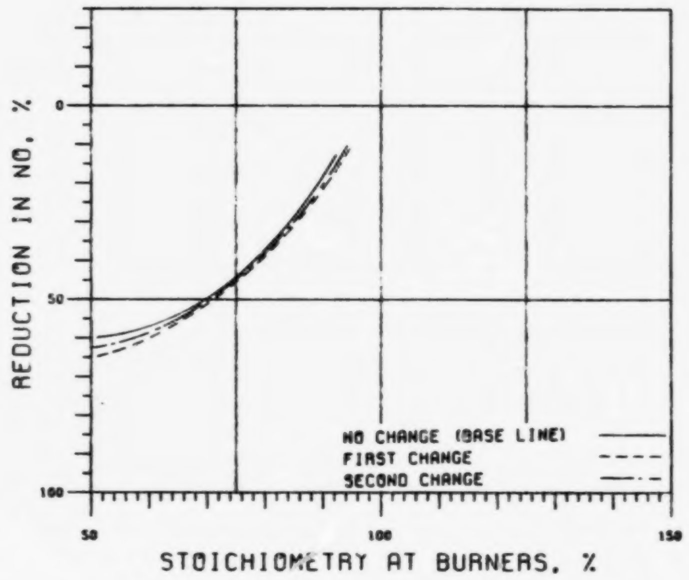

FIGURE 6.15 BURNER CHANGES — 15% AIR

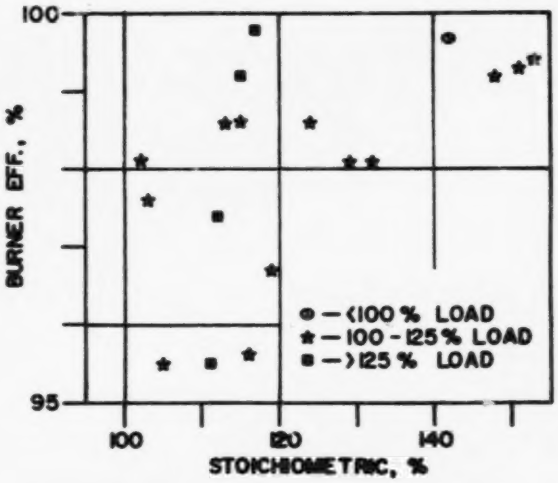

FIGURE 6.16 CARBON LOSS AND BURNER EFFICIENCY

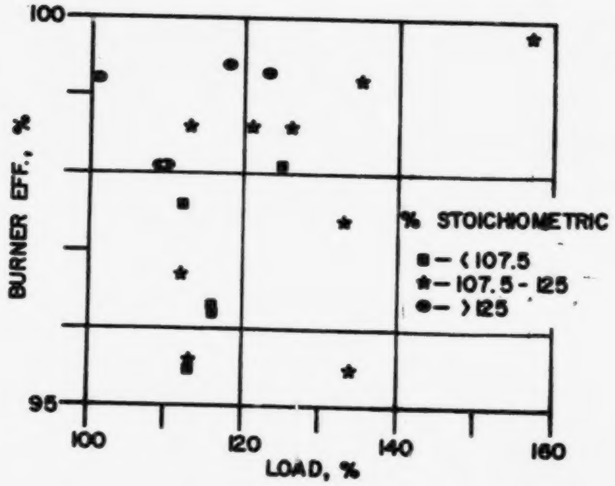

FIGURE 6.17 CARBON LOSS AND BURNER EFFICIENCY

VII. COMPARISON OF PHASE I AND PHASE II RESULTS*

The data variables which are to be compared in this section are shown in the following table:

Variables (x if tested)	Phase I Ohio Coal	Phase II Colorado coal	Phase I Natural Gas	To be Compared
Excess Air	x	x	x	yes
Load (heat release rate)	x	x	x	yes
Preheat	x	x	x	yes
Fineness		x		no
Swirl			x	no
Quench	x			no
Staged Combustion	x	x	x	yes
Flue Gas Recirculation	x	x	x	yes
Port Geometry		x		no
Burner Velocity		x		no

Each variable to be compared will be shown on a single figure and a table of results will be given in the text. These tables of results will be presented again, in duplicate form, in Section VIII, the Discussion.

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*The Phase I results for the Ohio coal and natural gas tests are taken from the Phase I Final Report, EPA 650/2-74-002a. The original data for Phase I used for comparison are in Appendix G.

Excess Air (Figure 7.1)

The comparison of NO emission level dependency on excess air for the three fuels follows:

	Colorado Coal	Ohio Coal	Gas
Effect	Major	Major	Strong
Average Emission (under standard conditions)	1100 ppm	700 ppm	300 ppm
Peak Position (percent excess air)	1350 ppm (35%)	1000 ppm (35%)	350 ppm (20%)
Variation from Maximum to	±350 ppm	±300 ppm	±65 ppm
Minimum Emission	650-1350 ppm	400-1000 ppm	220-350 ppm
Percent Variation About Mean	∼35%	∼40%	∼25%

The trends of the Colorado coal and the Ohio coal are qualitatively identical — the absolute NO levels are quantitatively different, however. Natural gas shows a different qualitative trend with peak NO emission levels at lower excess air.

Load (Figure 7.2, Rate of Heat Release)

The dependency of NO emission level on load or heat release rate resulted in:

Colorado coal — very strong effect; varied from 700-1150 ppm under normal conditions

Ohio coal — very strong effect; varied from 400-800 ppm under normal conditions

Gas — no dependence; 300 ppm under normal conditions.

The trends are almost identical for the two coals. The change over the whole range of load is about 400 ppm for both coals. Again, the trend for gas is different with the result that load is not a variable for gas.

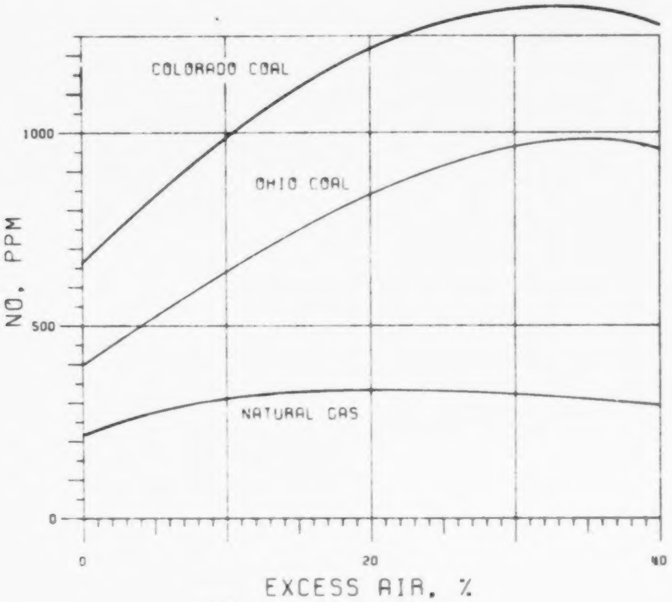


FIGURE 7.1 EXCESS AIR

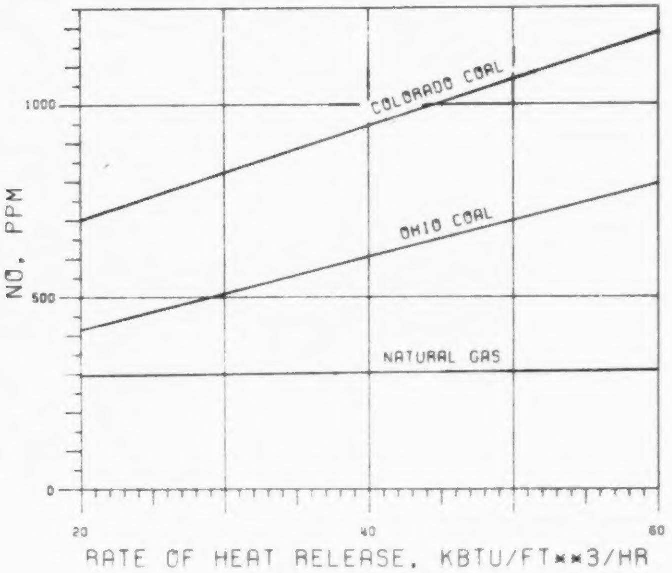


FIGURE 7.2 LOAD

Preheat (Figures 7.3 and 7.4)

Figure 7.3, for normal excess air yields the following dependence:

Fuel	Dependence	NO Range, ppm (Deviation about Mean)
Colorado Coal	Slight	925-1050 (∿6%)
Ohio Coal	None	725 (∿0%)
Gas	Strong	100-300 (∿50%)

On a part per million basis, the gas is most dependent at about 50 ppm/100°F slope to the line, Colorado coal is next with about 30 ppm/100°F slope, and Ohio coal is least dependent with 0 ppm/100°F slope. In general, the coals behave similarly on a percentage change basis; on a basis of quantitative change, no two of the fuels behave similarly.

At high excess air (Figure 7.4), the comparision yields the following:

Fuel	Dependence	NO Range, ppm (Deviation about Mean)
Colorado Coal	Slight	1100-1350 (±∿10%)
Ohio Coal	Moderate	750-1000 (±∿15%)
Natural Gas	Strong	100-300 (±∿50%)

The three fuels behave identically on a quantative basis; the slope of the lines is 50-60 ppm/100°F. On a percentage basis, the two coals behave similarly.

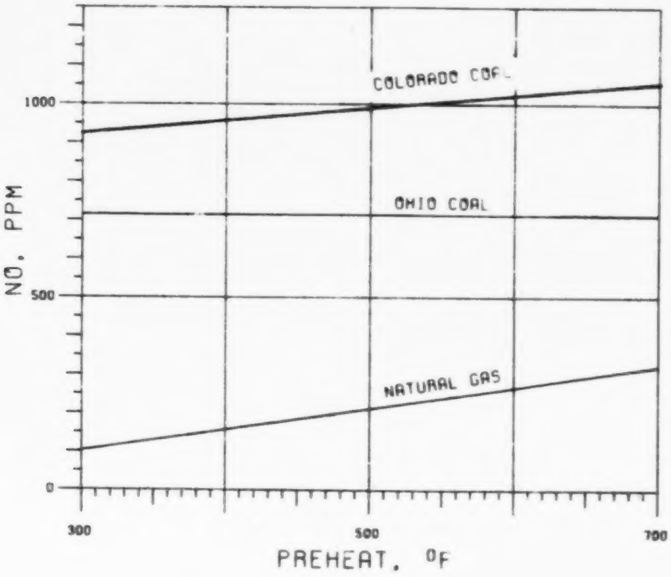


FIGURE 7.3 PREHEAT, NORMAL EXCESS AIR

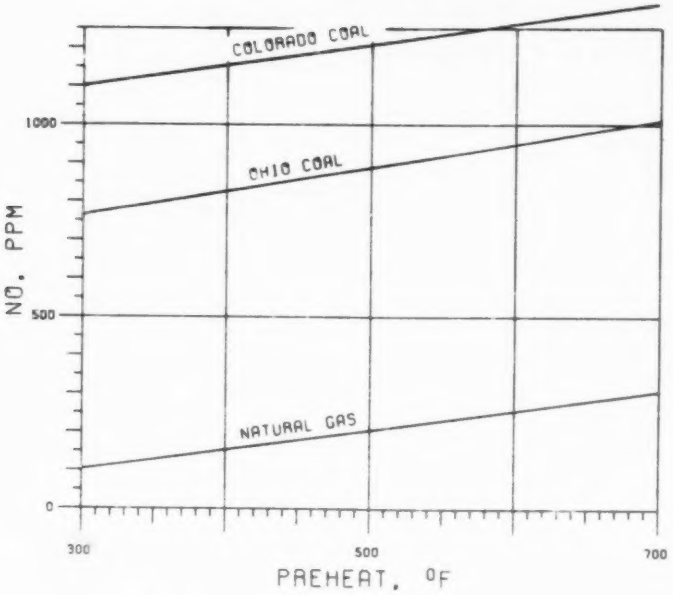


FIGURE 7.4 PREHEAT, HIGH EXCESS AIR

Flue Gas Recirculation (Figure 7.5)

The following results were observed for (secondary) flue gas recirculation:

Fuel	Effect	Reduction of NO, % (at 30% FGR)
Colorado Coal	Little	~12% (extrapolated)
(Ohio Coal (primary)	Little	<5% (at 5% FGR))
Ohio Coal (secondary)	Moderate	30%
Natural Gas	Very Strong	85%

Natural gas NO emission levels are greatly affected by flue gas recirculation. There is only a moderate effect on coal emissions at best.

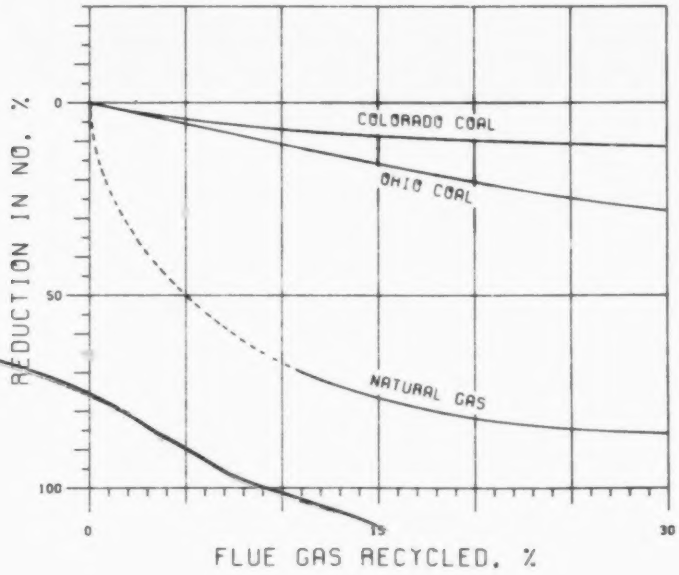


FIGURE 7.5 SECONDARY FLUE GAS REC.

Staged Combustion (Figure 7.6)

The results are:

	Colorado Coal	Ohio Coal	Gas
Normal Firing:			
Effect on NO	Strong	Strong	Very Strong
Maximum Reduction, %	70	60	90
Burner Air at Max. Red., % Stoich.	∿55	∿55	∿50(?)*
Substoichiometric:			
Maximum Reduction, %	100	100	100
Burner Air at Max. Red., % Stoich.	∿60	∿60	∿60
Variable Port Position	Some Effect (Not extended to low burner air for side ports)	Some Effect (Max. Red.: Side Ports 50 Front Ports 60)	No Effect

---

*Unknown if maximum reduction occurs at 50% air.

The substoichiometric curves for all three fuels are identical – the NO emission level goes to 0 ppm at 60% stoichiometry.

The reduction of NO emission levels for two stage combustion of all three fuels are similar between 60 and 115% stoichiometry at the burner. Below 60% burner stoichiometry, natural gas does not show a distinct valley in the curve at 50 to 60% burner stoichiometry. In addition, gas shows a greater maximum reduction than the two coals.

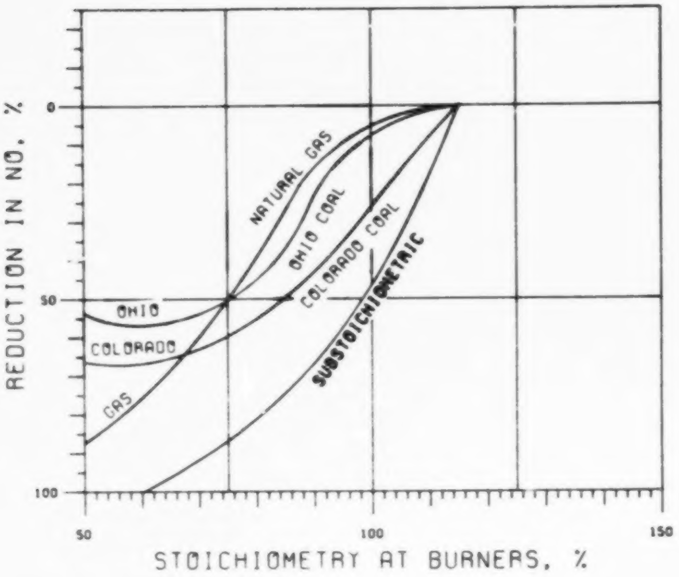


FIGURE 7.6 STAGED COMBUSTION

VIII. DISCUSSION

The discussion section is divided into four sections. These sections deal with the data results, special effects observed in the testing, final data discussion, and possible correlated interrelationships. The discussion presents the data as measured and interpreted.

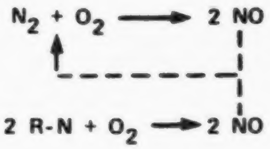
A. Results

The effects of each variable studied were usually straightforward for the Colorado coal when surveying a single variable; the simplest curve was drawn through the available data. These data were usually taken at the extremes and middle of the range for each variable; but in a few cases, only at the extremes of the range. In most cases, if a straight line did not fit the data, a slightly curving line did. It must be emphasized that in many cases the extremes of a single variable are beyond the range of what is currently considered acceptable operating practice. In addition, these results apply only to a small single burner test unit. Even so, it is believed that the trends will probably hold for large multiburner units, although the magnitude of these changes may be appreciably different. Finally, some of these variable changes may not be acceptable on large units.

In reviewing these results, it should be borne in mind that NO emissions are due to a combination of thermal fixation and fuel bound nitrogen conversion. During combustion of natural gas, only thermal fixation of atmospheric nitrogen is possible since there is no fuel bound nitrogen:

$$\begin{tikzcd} N_2 + O_2 \arrow[r] & 2\,NO \arrow[l, dashed, bend left] \end{tikzcd} \qquad (1)$$

(Only the overall formation is discussed here, not the mechanism of formation.) In contrast, coal contains fuel bound nitrogen and an additional source of nitric oxide is oxidation of this fuel bound nitrogen to NO:



$$N_2 + O_2 \longrightarrow 2\,NO \qquad (1)$$

and

$$2\,R\text{-}N + O_2 \longrightarrow 2\,NO \qquad (2)$$

where R is the fuel portion of the molecule.

The kinetic form of these equations is given by:

$$\text{from (1): } \frac{d[NO]}{dt} = k_{f,1}\,[N_2][O_2] - k_{r,1}\,[NO]^2 \qquad (3a)$$

$$\text{from (2): } \frac{d[NO]}{dt} = k_{f,2}\,[R\text{-}N]^2[O_2] - k_{r,2}\,[NO]^2 \qquad (3b)$$

where $k_{f,1}$, $k_{f,2}$, $k_{r,1}$, and $k_{r,2}$ are of the form:

$$k_x = A_x\,(T)^n\,e^{-E_x/RT} \qquad (3c)$$

(Note: by definition: $k_{r,1} \equiv k_{r,2}$)

It should be noted that the reverse reactions of (1) and (2) are identical and therefore it is not valid to say:

$$[NO]_{total} = [NO]_{(1)} + [NO]_{(2)}$$

if reactions (1) and (2) are considered separately. If this happens to be true for a given case, it is simply coincidential.

Excess Air

The results of the excess air tests show:

	Colorado Coal	Ohio Coal	Gas
Effect	Major	Major	Strong
Average Emission (under standard conditions)	1100 ppm	700 ppm	300 ppm
Peak Position (percent excess air)	1350 ppm (35%)	1000 ppm (35%)	350 ppm (20%)
Variation from Maximum to Minimum Emission	±350 ppm 650-1350 ppm	±300 ppm 400-1000 ppm	±65 ppm 220-350 ppm
Percent Variation About Mean	∿35%	∿40%	∿25%

The Phase I results, showed that there were significant differences in the NO emission levels of gas and the Ohio coal which are at least partially attributable to fuel bound nitrogen. Although there are differences between the two fuels in flame temperature, combustion rate, physical state of the fuel, and even gas velocities, these differences would be expected to produce less change in NO_x than the fuel bound nitrogen. In particular, the difference in the shape of the curve is expected to be a change due to fuel bound nitrogen.

The NO emission from gas, the thermal fixation of atmospheric nitrogen, depends upon temperature and excess air level. At low excess air levels, the effect of increasing oxygen level more than offsets the decreasing flame temperature, thus the curve initially rises. In addition, the flame can be more luminous at lower excess air level; this can lead to more rapid quench rates. At high excess air levels, the decreasing temperature becomes the overriding effect and the curve drops after passing through a maximum.

In contrast, the coal, which contains fuel bound nitrogen as a second source of NO, shows both a different position of an NO maximum which is shifted to higher excess air, and an increase in formation of NO at all excess air levels. These differences are, at least qualitatively, due to the fuel bound nitrogen. The trend thus shown indicates a positive correlation between increasing fuel bound nitrogen conversion to NO and increasing excess air. It is felt that the fuel bound nitrogen conversion cannot be quantitatively evaluated. (An additional factor is the apparent greater luminosity, and therefore greater rate of radiation, of the coal flame as compared to the gas flame at low excess air. Also, the coal flame luminosity appears to be insensitive to excess air level whereas the gas flame luminosity is very greatly dependent upon excess air.)

The Colorado coal shows the same qualitative dependence upon excess air as the Ohio coal. But quantitatively, the NO emission levels from the Colorado coal are 25% to 50% higher than from the Ohio coal. In addition, the Colorado coal had a different type of flame structure than the Ohio coal. Under normal or high excess air, the flame was clear, like a natural gas flame, and almost nonluminous. Only at low excess air did the flame become similar to the large, luminous Ohio coal flame.

The overall differences between the Ohio and Colorado coals are:

1) Less luminosity of the Colorado coal flame (this would be expected to cause the Colorado coal to have a higher flame temperature than the Ohio coal)

2) Higher (wet) Btu content of the Colorado coal (this would also be expected to yield a higher flame temperature)

3) Lower sulfur content of the Colorado coal.

The fuel bound nitrogen content of the Colorado coal is about the same in quantity as the Ohio coal; both have ∿1.1% fuel bound nitrogen by weight.

The Colorado coal curve is the same shape as the Ohio coal curve and so, qualitatively, the increase in the NO emission at any given quantity of excess air was probably due to a change in the conversion of fuel bound nitrogen to NO. This could have been due to any or all of the following for the Colorado coal (as compared to the Ohio coal):

1) The flame structure at higher excess air levels indicated more rapid combustion due to shortened flame; and probably with higher flame temperature, at least momentarily during the initially more rapid burning

2) The flame structure indicated more complete combustion (as does the stack measurement of burner efficiency) due to clearer flame and less carbon emission in the flame

3) The Colorado coal could have a greater fraction of the fuel bound nitrogen as a volatile nitrogen content (as opposed to a nonvolatile slow burning char content)

4) No. 1). 2) and 3) would imply a lower residence time for the reduced fuel bound nitrogen constituents in a reducing atmosphere and less carryover of these reduced species

The overall result could be 1) increased conversion of fuel bound nitrogen to NO, due to lack of time for recombination to N_2 or reduction to N_2; 2) higher rate of reaction of fuel bound nitrogen fragments to NO, due to higher temperature; and 3) higher free radical concentrations, as would be observed from the higher temperatures. These conclusions agree with the NO levels of the Ohio and Colorado coals which tend to differ less at low excess air where the flame patterns tend to become similar. The staged combustion results also indicate this since two stage combustion on the Colorado coal, although giving somewhat greater percentage NO reduction than the Ohio coal (60 to 75% versus 50 to 60%), tends to yield about the same absolute NO emission levels, in ppm, as the Ohio coal when the flame patterns are almost identical.

However, it may be argued that the increase of NO emission level is due to thermal conversion of atmospheric nitrogen from the higher flame temperature. This is definitely a contributor to the higher NO emission level, but the question is, is it the major source of NO increase? (The fuel bound conversion is not likely to be the only contributor to the increased NO emission because the overall increase is about 350 ppm at 35% excess air (1000 ppm versus 1350 ppm absolute for the Ohio and Colorado coals respectively), and at a 1% fuel bound nitrogen equivalence of 2300 ppm NO for total conversion, this would indicate a 15% increase in the fuel bound nitrogen conversion efficiency from the Ohio to the Colorado coal.) There are three fundamental reasons for believing that the increase is not primarily due to increases in thermal NO:

1) The shape of the curve does not show a dependence on flame temperature between 20% to 30% excess air (at constant flame luminosity) where a thermal conversion peak would be expected. The shape of the Colorado coal curve matches the Ohio coal

curve and does not show an intermediate shape between the Ohio coal and natural gas. For natural gas, beyond 20% excess air, the lower temperature at higher excess air levels indicates stronger dependence on temperature than on excess air — not the case for the coal curves.

2) The high NO levels from the two coals are not unrealistic and would be compatible with a 25% to 50% fuel bound nitrogen conversion to NO. This would correspond to 600 ppm to 1250 ppm for a 1.05% to 1.15% nitrogen coal. (This should not be interpreted as a quantitative evaluation of the fuel bound nitorogen conversion to NO. It is a relative estimate only.)

3) The ineffectiveness of flue gas recirculation indicates that this increase is not due to thermal NO since the flue gas recirculation would have been more effective for the Colorado coal than for the Ohio coal since flue gas recirculation reduces thermal NO significantly.

Finally, it cannot be ruled out that the change in NO_x is due to a synergistic effect caused by the reduced sulfur content. Some preliminary, unpublished results of other investigators indicate that higher sulfur levels can lower NO emission levels. Although this is a possible explanation for the difference in NO emission levels for the Ohio and Colorado coals, it can be neither proven nor disproven by the results of this study.

Load

The result of load change shows:

Colorado coal – very strong effect; varied from 700 - 1150 ppm under normal conditions

Ohio coal – very strong effect; varied from 400-800 ppm under normal conditions.

Gas – No dependence; 300 ppm under normal conditions.

Again it should be pointed out that with the burner arrangement used for these tests, both the air velocity through the burner and the turbulence changed with load. However, there is no indication of a peak level having been reached under increasing load conditions. (There is refractory shielding in the front half of the furnace.) The two coals respond in a similar manner with identical qualitative trends (the rate of change over the whole range is 450 ppm for the Colorado coal and 400 ppm for the Ohio coal).

Preheat

The dependence of NO emission level on air preheat is interesting. Normal conditions (15% excess air and 100% load) result in:

Fuel	Dependence	NO Range, ppm (Deviation About Mean)
Colorado coal	Slight	925-1050 (~6%)
Ohio Coal	None	725 (~0%)
Gas	Strong	100-300 (~50%)

and for high excess air and normal load:

Colorado coal	Slight	1100-1350 (±~10%)
Ohio coal	Moderate	750-1000 (±~15%)
Gas	Strong	100-300 (±~50%)

The indication from the natural gas is that thermal production of NO is increasing at a rate of about 50 ppm per 100^{0}F preheat increase regardless of excess air level. This is determined from the total change over the range of the curve for gas. This same type of increase of thermal emission of NO should, but does not, occur for the Ohio coal and for the Colorado coal. Both coals would be expected to show the same effect on preheat by excess air as gas. Since little is known of the local temperature history of the flames any conclusions based on these observations would be very speculative.

The different dependence of the Colorado and Ohio coal preheat curve slopes on excess air can be considered on either a ppm basis or a percentage basis. The normal excess air to high excess air responses of the preheat curve slopes for the Ohio and Colorado coals are:

	Slope of preheat curve normal excess air range		Slope of preheat curve high excess air range	
	%*	ppm	%	ppm
Ohio coal	+ 0	+ 0	+ 15	+ 125
Colorado coal	+ 6	+ 65	+ 10	+ 125

The effect of the flame temperature change would probably explain the different preheat dependence, for the two coals, especially at the normal excess air level of 15% below which the flame color, shape, and luminosity begin to change.

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*Expressed as a deviation about the mean: i.e., in the previous table, Colorado coal showed a range of 1100 to 1350 ppm at high excess air from low to high preheat. The mean (straight line) is 1225 ppm and the deviation about the mean is + 125 ppm (or ± 10%).

The indication from the natural gas is that thermal production of NO is increasing at a rate of about 50 ppm per 100^{O}F preheat increase regardless of excess air level. This is determined from the total change over the range of the curve for gas. This same type of increase of thermal emission of NO should, but does not, occur for the Ohio coal and for the Colorado coal. Both coals would be expected to show the same effect on preheat by excess air as gas. Since little is known of the local temperature history of the flames any conclusions based on these observations would be very speculative.

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	Slope of preheat curve normal excess air range		Slope of preheat curve high excess air range	
	%*	ppm	%	ppm
Ohio coal	± 0	± 0	± 15	± 125
Colorado coal	± 6	± 65	± 10	± 125

The effect of the flame temperature change would probably explain the different preheat dependence, for the two coals, especially at the normal excess air level of 15% below which the flame color, shape, and luminosity begin to change.

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*Expressed as a deviation about the mean: i.e., in the previous table, Colorado coal showed a range of 1100 to 1350 ppm at high excess air from low to high preheat. The mean (straight line) is 1225 ppm and the deviation about the mean is ± 125 ppm (or ± 10%).

Fineness

Fineness is not a major variable in our basic combustion unit when comparing the excess air, load, or preheat as variables. The slight variation curve for any one of the variables is less than 5% and less than the maximum error of measurement or reproducibility.

Flue Gas Recirculation

The following results were obtained for flue gas recirculation:

Fuel	Effect	Reduction of NO, % (at 30% FGR)
Colorado coal	Little	~12% (extrapolated)
Ohio Coal, primary	Little	<5% (at 5% FGR)
Ohio coal, secondary	Moderate	30
Gas	Very Strong	85

Since the primary transport air for coal represents about 15% of the total combustion air, a high level of primary flue gas recirculation is not possible, even if a maximum amount of primary flue gas substitution is used. Primary flue gas recirculation did not significantly lower the NO emission levels for the Ohio coal tests. For this reason, primary flue gas recirculation was not run with the Colorado coal. In addition, primary flue gas recirculation experience with the Ohio coal resulted in decreased burner performance and ignition problems. It is felt, however, that any reduction of NO on coal fired units by use of this approach is relatively insignificant. The effect of flue gas recirculation on the Colorado coal indicated little or no reduction of NO emission levels. Addition of 10 to 15% flue gas recirculation reduced the NO emission levels in the Ohio coal by 10 to 15% and in the Colorado coal by 5 to 10%.

The overall effect of flue gas recirculation (secondary flue gas recirculation for coal) appears to be reduction of thermal NO emissions as evidenced by the natural gas data. The effect of flue gas recirculation on conversion of fuel bound nitrogen is unknown, but the reduction of this component is probably minimal.

Staged Combustion

The results of the staged combustion data are as follows:

REDUCTION IN NO, %

Staging Test	Colorado Coal	Ohio Coal	Gas
Normal:			
Effect on NO	Strong	Strong	Very Strong
Maximum Reduction	70	60	90
Burner Air at Max. Red., % Stoich.	∿55	∿55	∿50?*
Substoichiometric:			
Maximum Reduction	100	100	100
Burner Air at Max. Red., % Stoich	∿60	∿60	∿60
Variable Port Position	Some effect (Not extended to low burner air for side ports)	Some effect (Max. Red.: Side Ports 50 Front Ports 60)	No effect

The difference in the second stage port position was moderately important for the Colorado coal firing tests. Although the reduction of NO is not significantly different numerically at lower burner to total air ratios** for the two slot positions, the visible flame pattern indicated a low second stage combustion efficiency for the side slots. In particular, a large cylindrical, highly turbulent flame envelope surrounded a blacker carbon containing core. Carbon became visible in the smoke from the stack. Therefore, only the front slot, or "progressive combustion" data are used for discussion of further results.

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*Unknown if maximum reduction occurs at 50% air.

**The burner to (total) air ratio is defined as the weight of air through the burner divided by the total weight of air into the furnace.

It should be noted that these staged combustion data were obtained with fixed burner and slot openings. Thus, as the burner to total air ratio decreased and staging increased, the air velocity through the burner decreased and the air velocity through the ports increased. It is for this reason that the performance and the effect on two stage combustion was unsatisfactory at lower burner to air ratios when using the side slots.

The greatest effect of staging was found with gas. Almost all of the NO was eliminated by staging the gas combustion. (The addition of flue gas recirculation can remove all or most of the rest of the NO emission.)

Coal tests showed reduction of up to 60% of the NO emission levels for staged combustion. An apparent maximum reduction of the NO is reached at about 50% burner to total air ratio. This minimum is not unexpected because it represents the diminishing return on the reduction of the thermal NO precursors and conversion of the fuel bound nitrogen in the first stage as contrasted to increasing thermal NO formation in the second stage due to increasing enthalpy release in the second stage combustion. In addition, it is possible that significant amounts of fuel bound nitrogen fragments (such as HCN, CN, etc.) may be formed which survive long enough to be oxidized to NO in the second stage.

An attempt was made to determine if a valley in the reduction curve for coal emissions really exists at the 50%-60% burner stoichiometry. Although the curve leveled out below 70% burner stoichiometry, it never clearly indicated a rise from the curve valley again, even down to 45-50% burner stoichiometry.

The substoichiometric tests for gas and the two coals, when superimposed, are the same curve and intercept 100% reduction of NO emission level (0 ppm NO) at 60% of stoichiometry. These results seem to mean that both thermal NO formation and fuel bound nitrogen conversion to NO under substoichiometric combustion conditions have the same final precursors in atomic or free radical form such as NH, N, etc. In other words, the reactions directly leading to NO are independent of the source which provides these free radicals. In addition, it would appear that there is a lower level of burner air below which NO formation in the first stage drops to zero and it is of no further use to decrease the burner to air ratio. Obviously, this is a function of second stage geometry, spacing, gas temperature, etc. Actual staged tests indicate that the residence time in the first stage is really too short and a greater physical separation is required between stages. If so, the burner area may not be the place to add second stage air. An alternative might be to increase swirl and mixing in the first stage, but increased temperature and combustion intensity will result.

Slot Changes

Little or no effect on NO emission levels was observed for the slot changes which were made. It would appear from observation of the NO emission levels and the reduction of these levels that there was no overall effect. However, two of these modifications greatly affected the combustion patterns.

The angling of the front slots outward had little effect except to somewhat broaden the oblong shape of the flame. The inward angling (the first change) showed an extreme change in flame pattern: the first stage combustion was wiped out and a new long, circular pattern of flame appeared. Apparently, the internal recirculation zones of the first stage combustion extended up to and beyond the intersection of the second stage addition of air and the burner air; the result was loss of ignition at the burner and ignition held (by hot wall radiation and new post burner recirculation patterns) at the intersection of the two air streams. The combustion pattern showed up as a new longer, lazier, single stage combustion pattern.

Both changes in the side slots involved a halving of the radius of the "circle of air injection" for the second stage air. At the center of the flame, the smokey core surrounded by a bright firing halo disappeared and the overall flame became thoroughly bright with little or no radial changes apparent.

In testing the effect of port position for staging, no significant difference in NO emission levels from the side or front ports was observed. All points were used to draw a single curve.

Burner Changes

The effect of velocity on NO emission levels was minimal. The effect of velocity on overall excess air levels, load levels, and preheat levels showed some slight variation, but this was less than the error in the experimental measurement.

The effect of burner velocity on the staged combustion tests was also unimportant. In general, it appears that velocity is not a major variable in our basic combustion unit.

The flame patterns were usually unaffected by the velocity changes.

B Data and Testing Effects

NDIR/TECo

The NDIR and TECo instruments are very easy to use and require only minimum maintenance. Both instruments or one instrument and another independent method of NO measurement should be used at the same time. Either instrument may slowly drift away from the true NO measurement and require recalibration. An indication of some problem is indicated almost immediately when the instruments do not agree on an NO measurement. The most common problems encountered were due to changing temperature in the furnace area where the instrumentation is located:

1) Loss of the temperature controller on the NDIR and subsequent drift.
2) Loss of calibration on the TECo due to increased temperature and an increase in the dark current.
3) Loss of NO in the 34^{o}F ice bath at the highest excess air levels.

Any of these problems for either instrument is easily corrected if it is recognized; during our testing all of these problems were easily identified.

Temperature changes in the furnace room were unavoidable and since the instrumentation was in the same area, it was inevitable that these changes affected the TECo and NDIR. These changes were minimized by calibrating after the furnace was warmed up and the room became hot.

Preventative maintenance eliminated almost all other problems that had appeared in Phase I with the instruments. Whenever measurements were made, the instruments had to agree within ± 10 ppm or ± 5%

(whichever is larger) or a problem was suspected and the situation corrected. Calibration checks were made several times a day and usually no significant drift for either instrument over a single day was noticed. When a drift was noticed it was usually due to one of the three problems listed above and recalibration solved the problem.

The only gaseous interferent observed for either instrument was H_2O which absorbs infrared like NO when measured by the NDIR. The presence of CO with NO does not reduce the NO measurement, even when passed through the heated stainless steel coil used for the NO_2 conversion in the TECo.

It was noticed that the NDIR/TECo error is greatest at the highest excess air levels. Inevitably, the NDIR read low when compared to the TECo. In some cases this error exceeded 5% and could not be reconciled with any calibration checks. Recently some time was spent working on this problem and the results were:

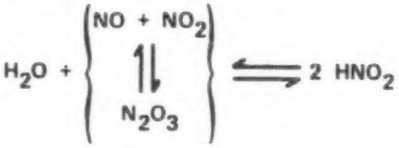
1) NO_x disappeared in the 34°F ice bath but not to any large extent in the 50°F ice bath, although the smell of NO_2 was present in the 50°F bath.

2) When the flue gas was replaced by air, there was a "lingering, but decreasing" NO level recorded on the NDIR and TECo from the 34°F ice bath.

3) When the 34°F cold finger was opened, a strong smell of NO_2 was present on warming.

4) No increase of NO (from the 50°F ice bath) was indicated by the TECo.

It is suspected that at 34°F the glass surface may aid in oxidizing NO to NO_2, especially at high levels of excess air where the oxygen concentration is 7% (versus 3% and <1% at lower excess air levels) and then NO_2 dissolves in the water of condensation to produce nitrous acid:



$$H_2O + \left\{ \begin{matrix} NO + NO_2 \\ \upharpoonleft\downharpoonright \\ N_2O_3 \end{matrix} \right\} \rightleftharpoons 2\ HNO_2$$

In addition, irreversible oxidation to nitric acid is also possible:

$$O_2 + 2\ HNO_2 \longrightarrow 2\ HNO_3$$

Whittaker (NO_x)

The Whittaker chemical cell NO monitor has shown unreconcilable differences when compared to readings from the NDIR and TECo during most coal testing. It did not respond to the true NO levels in the flue gas. Although it read correctly at times, it did not do so consistently. When the reading was in error (greater than ± 10% deviation), it always read a value higher than the NDIR and TECo. This higher reading cannot be reconciled and it does not seem to involve the following:

1) Calibration – This was checked even before and after bad measurements.

2) SO_2 – Fresh Malcosorb and calibration steps rule this out because of the very rapid response.

3) CO/CO_2 – Test gases with these, even when saturated with water, had no effect except at very high concentrations of CO (>1% CO).

The higher reading appears to be the result of some component in the flue gas which is not taken out completely by the filters, water bath, or Malcosorb. Substitution of Dynascience's "SO_2 Scrubber Solution" in a normal bubbler did not remove the interferences in the NO measurement either. The solution bubbler made the instrument somewhat more erratic and the maximum errors in any single reading seemed greater. The average error of all readings appeared to be somewhat lower with the bubbler, however.

Fluctuation in Coal Data

From day to day, changes in the NO emission levels for duplicate tests occurred. The causes of these changes are unknown. The following suggestions have been made, but it is not known if these even contribute to the problem:

1) Air temperature variations (no air preheat in primary)

2) Changes in air humidity

3) Moisture variations in coal

4) Slight changes in fraction of total air used for primary coal transport (changes primary air to coal weight by a much larger amount)

5) Changes in the coal, chemically, as day by day slightly different grindings are used.

The magnitude of these changes is usually less than the error of measurement (± 5%) but can sometimes become ± 10%. It was considered not to be a major problem however and was usually ignored.

Carbon Loss

The carbon loss (as opposed to burner efficiency) from the coal fired tests on our unit (there is no observable solid carbon loss during oil or gas fired tests on our unit) is dependent upon the excess air. The efficiency for the combustion of the Colorado coal was above 95% and usually about 98%.

C. Final Presentation

Table 8.1 shows the final results for the Phase II studies. This table is used to indicate the effect of each variable on NO emission levels. The number of pluses or minuses is meant only to be a relative indication of NO reduction.

D. Interrelated Variables

Some of the variables are interrelated and should be considered only in combination. (For example, see preheat and excess air effect upon preheat as shown in Table 8.1.) In addition, many of the variables studied could be defined by a new set of variables such as enthalpy content, temperature, velocity, etc.

TABLE 8.1 RELATIVE EFFECTS ON NO IN THE FLUE GAS*

	Phase II	From Phase I	
Under Normal Conditions Increasing Level of Variable	Colorado Coal	Ohio Coal	Gas
Excess Air	++++	++++	++/--
Load	+++	++++	0
Preheat (normal air)	++	0	+++
(high air)	+++	+++	+++
Fineness	0	no data	no data
Flue Gas Recirculation	-	--	----
Staged Combustion	----/	----/	---
Slot Changes (added effect)	0 to +	no data	no data
Burner Changes (added effect)	+ to 0	no data	no data

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*+ Indicates increasing; number of +'s indicates relative magnitude
- Indicates decreasing; number of -'s indicates relative magnitude.
/ Indicates maximum or minimum is reached.

IX. CONCLUSIONS

The following conclusions have been derived from the work performed in Phases I and II for coal firing on the single burner test unit:

1) There is a distinct difference in NO emissions from the Ohio and Colorado coals attributable to fuel bound nitrogen and possibly flame temperature.

2) The conversion of fuel bound nitrogen increases with increasing excess air level for both coals.

3) Air preheat affects the coal NO emission levels differently for different excess air levels. The reasons for this are unknown.

4) A very small reduction of NO for the Colorado coal and a moderate reduction for the Ohio coal for secondary flue gas recirculation has been shown, and apparently only thermally formed NO is reduced.

5) A minimum of 60% burner air (total burner to 100% theoretical air) for reduction of NO is indicated for staged combustion of both coals. No further first stage reduction of NO seems to occur at lower percentages of burner air.

6) A definite physical separation appears to be required for addition of the second stage air for reduction of NO from coal combustion. Progressive

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mixing may be adequate. Even so, a separately spaced second stage probably is better.

7) It appears that the same free radicals are responsible for conversion of fuel bound nitrogen and thermal fixation of NO in the final steps of NO production under substoichiometric conditions.

8) It has not been possible in Phase II to determine quantitatively what fraction of the NO is from fuel bound nitrogen for either coal. About 10%-15% more of the Colorado coal fuel bound nitrogen appears to be converted to NO than for the Ohio coal.

The final conclusions to be drawn from the Phase I and Phase II work shows that for coal testing on our basic combustion unit and applicable to single burner units (no consideration of burner design is attempted):

1) Thermal fixation/fuel bound nitrogen conversion NO emission effects are different. Conditions to reduce one source of NO are not the same as those to reduce the other.

2) Flue gas recirculation does not show promise for NO reduction in coal flames.

3) For existing units, excess air level shows the most promising means of controlling flue gas emissions of NO.

4) For new units, staged combustion and total air control show the most effective means of reducing NO emissions.

5) The second stage air probably should not be added with the burner air for greatest effect, but from separate NO_x ports.

X. REMARKS (Recommendations)

The indications from the Phase I single burner work have been reinforced by the Phase II single burner work. The most promising NO reduction method for existing units without construction or costly modification is control of excess air. This requires lowered excess air, probably below 10%. Another method for new units is staged combustion. Again the requirement appears to be a separate first stage with reducing conditions prevalent. Since these concepts require a change in overall utility design and manufacturing, there will be a long period of development and testing required to demonstrate the practicality of these ideas. Much of the problem will be fears of increased corrosion (which may or may not be substantiated in the future), increased carbon loss, decrease in burner stability (which may or may not exist), slagging, etc. There is a need for continuing research so that the anticipated problems either can be shown to be nonexistent or can be solved by the utility and manufacturing people.

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APPENDIX A

FUELS DATA, ANALYSES, AND CALCULATIONS

A. Fuel Data

The coal used in all of our coal fired tests during Phase II was a Colorado coal from the Bear Mine in Somerset Colorado. The time lag for an analysis was at least 30 days from the time of submission of samples. Therefore all calculations pertaining to stoichiometry and load were carried out based on a prior, but recent coal analysis. This analysis and the average moisture used in calculations are shown in Table A.1. Although there was some variation in the moisture analyses, the calculations were not corrected since any error was considered smaller than the experimental measurement techniques.

The natural gas analysis used for the igniter is shown in Table A.2. The analyses first used were averaged and all calculations based on these numbers. Later, a new analysis was found and although the molecular constituents were about the same, the density and Btu value were different. However the new analysis was not used in the calculations due to the small effect that the igniter gas would have in the coal fired tests.

In addition to those analyses listed in Table A.1, other coal fuel bound nitrogen and moisture analyses were also run. Below follows the listing of these:

Coal			
Date of Sample	2/13/74	3/18/74	4/11/74
Nitrogen, % dry	1.2	--	--
Moisture	4.9	5.3	5.6

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B. Fuels Analyses

No fuels analyses were done at B&W ARC for natural gas. All values were reported to B&W by the Columbia Gas Company at regular intervals.

All of the important fuels analyses for coal are shown below by the method used at B&W ARC:

Moisture	ASTM by heating and weight difference in samples
Btu	ASTM by bomb calorimetry
Total – carbon	ASTM by collection of CO_2 in ultimate train
– hydrogen	ASTM by collection of H_2O in ultimate train
– nitrogen	Kjeldahl distillation and titration
– sulfur	ASTM by bomb calorimetry washings as $BaSO_4$
– ash	ASTM by complete combustion and residual weight
– oxygen	By difference

C. Fuels Calculations

In the chemical description of the coal for mathematical purposes, all weight percent contents including moisture were converted to atomic percentages. The ash was considered to be SiO_2. An ash analysis indicated large amounts of Al_2O_3 and Fe_2O_3 and so the SiO_2 was a good average in molecular weight between $AlO_{1.5}$ and $FeO_{1.5}$. The fuel values on conversion showed the following atomic ratios for chemical balance at stoichiometric conditions:

Colorado coal (wet) — C = 1.0000   Stoichiometric Air (dry) — N = 8.6808
H = 0.91614   O = 2.3273
N = 0.01408
S = 0.00564
Si = 0.02680
O = 0.19563

Natural gas — C = 1.0000   Stoichiometric Air (dry) — N = 14.639
H = 3.8851   O = 3.9267
N = 0.0087
O = 0.0158

(For reference, the following are included:

Ohio coal (wet) — C = 1.0000   Stoichiometric Air (dry) — N = 9.1830
H = 0.94309   O = 2.3294
N = 0.01328
S = 0.01504
Si = 0.03519
O = 0.24269)

The theoretical air requirement for the coals and gas above yielded a curve of excess air versus oxygen concentration in the flue gas after combustion had taken place. Suitable curves were chosen* rather than calculating each case separately. The curves chosen are:

Either coal: If $0.0 \leq \%\ O_2 \leq 2.5102$

Then $PTA = 100 + 4.7279\ (POF)$

If $\%\ O_2 > 2.5102$

Then $PTA = 100 + \frac{10}{3}\ (POF) + \frac{5}{9}\ (POF)^2$

Gas: If $0.0 \leq \%\ O_2 \leq 2.4588$

Then $PTA = 100 + 4.7279\ (POF)$

If $\%\ O_2 > 2.4588$

Then $PTA = 100 + \frac{7}{2}\ (POF) + \frac{1}{2}\ (POF)^2$

where: PTA = % theoretical air

and POF = % oxygen as measured in the flue gas

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*Useful Tables for Engineers and Steam Users, 11th Ed., 1969, The Babcock & Wilcox Company.

The two sizes of Colorado coal used in the fineness tests were:

Percent through	Coarse (Series VII, IX, X, XI, and XII)	Fine (Series VIII)
30 mesh	99.6	99.7
50	98.5	99.2
100	91.8	98.5
140	81.5	96.1
200	70.0	91.6
270	58.8	85.2
375	50.0	76.8

The coarse pulverization was used for all Colorado coal tests except Series VIII.

TABLE A.1 COLORADO COAL ANALYSIS

B&W Lab Serial No.	C-13864	--	--	Average	C-13864
Date	2/11/74	3/5/74	2/13/74		3/17/75
% Volatile	--	--	--		38.5
Fixed Carbon	--	--	--		52.6
Ash	9.8	--	--		8.9
% Total Moisture	4.4	4.1,5.2	4.9	4.65	3.3
Btu/lb, Dry	12980	--	00		--
Ultimate, Dry %					
C	73.1				
H	5.1				
N (determined)	1.2				
S	1.1				
Ash	9.8				
O (difference)	9.7				

TABLE A.2 NATURAL GAS ANALYSIS

Type	Columbia Gas Transmission Corp Pittsburgh Group, Steubenville			Average of three groups	New Analysis (Not Used)
Date	12/20/71	6/21/71	1/23/71	--	12/18/72
Mole %*					
N_2	0.47	0.40	0.49	0.45	0.40
CO_2	0.72	0.97	0.77	0.82	0.78
CH_4	95.01	95.57	95.08	95.22	95.84
C_2H_6	3.19	2.63	2.93	2.92	2.54
C_3H_8	0.41	0.30	0.49	0.40	0.30
C_4H_{10}	0.15	0.10	0.19	0.15	0.11
C_5H_{12}	0.05	0.03	0.05	0.04	0.03
C_6H_{14}*	--	--	--	--	--
$\rho_{(calc.)}$	0.5864	0.5835	0.5872	0.5857	0.5814
Btu (calc.)	1038.7	1029.0	1038.1	1035.3	1030.5

*Sulfur bearing materials were small and therefore not entered into the calculations.

TABLE A.3 OHIO COAL ANALYSIS

COAL ANALYSIS DATA

B&W Lab Serial No.	C-13688	C-13689	C-13692	Average Used in Calculations	C-13762 (Not used in Average)
Date of Sample	4/20/72	5/9/72	5/15/72	--	1/18/73
% Volatile	38.6	38.1	39.6	--	--
Fixed Carbon	49.4	48.7	49.2	--	--
Ash	12.0	13.2	11.2	--	--
% Total Moisture	5.7	6.4	6.3	6.13	5.4
Btu/lb, Dry	12290	12020	12410	12240	--
Ultimate, Dry %					
C	69.1	67.9	69.7	68.9	72.8
H	4.8	4.6	4.9	4.77	5.0
N (determined)	1.1	1.0	1.1	1.07	1.1
S	2.8	2.7	2.8	2.77	--
Ash	12.0	13.2	11.2	12.1	7.6
O (difference)	10.2	10.6	10.3	10.4	--

APPENDIX B

OPERATING CONDITIONS, MEASUREMENTS, AND CALCULATIONS

A. Operating Conditions

Before any data runs for a day's testing commenced, the furnace was warmed up and all instruments were calibrated. The furnace warmup period was at least one half to one hour. During this time, all instruments were zeroed and calibrated with at least one standard gas.

The NO_x instrumentation was checked with at least three or four Matheson gas standards of ∿200, ∿500, ∿800, and ∿1300 ppm NO in nitrogen. As standard tanks of gas neared the point of being empty, new standards of the same concentration were ordered with a certified analysis. These new standards were checked against the old ones to verify the analysis before use as calibration gases.

The standard operating conditions selected for our basic combustion tunnel were 115% theoretical air, $600^{\circ}F$ preheat for the secondary air, and a 5,000,000 Btu (5 MBtu)/hour load or heat release rate. During all coal tests, the natural gas igniter was operated at three lb/hr and a heat release rate of about 70,000 Btu (70 kBtu)/hr.

B. Calculations

The orifice calculations used are based on the ASTM Fluid Meter Report, 1940. The important equations are:

$$W = 358.9\ (D_1)^2\ KEY\ \sqrt{\rho_{true}\ \Delta H}$$

where:

$$KEY = 0.935\ (0.7 - D_1/D_2)^{5/4} + D_1/D_2$$

and

$$\rho_{true} = 0.0741\ \frac{273.16\ (P_{net})}{0.55556\ (T + 459.67)}$$

For all inlets the air calculations for the furnace firing reduce to:

$$W = K \sqrt{\frac{(PS)(\Delta H)}{T + 459.67}}$$

Where:

Dry air inlet description	D_1	D_2	K, a constant
Primary air	2.25	4.00	7028.
Secondary air	7.0	12.0	68689.
Secondary flue gas	5.0	12.0	33601.
Second stage air	4.5	8.0	28110.

The addition of humidity in the air is easily accomplished:

$$W_{H_2O} = W_{air} \sqrt{\frac{(\rho_{H_2O})(PS_{H_2O})}{(\rho_{air})(PS_{air})}}$$

$$= W_{air} \sqrt{0.62133\ \frac{PS_{H_2O}}{PS_{air}}}$$

Where:

W_{H_2O} is the weight of water in lb/hr

and

W_{air} is the weight of air in lb/hr (previously calculated above)

The ash sampling probe also reduces to the same type of equation whereby D_1 is 0.625, D_2 is 1.5, and K is 525.3. For the natural gas igniter, the orifice equation is:

$$W = \frac{10.0^{(0.61278 + \log(NF))} \cdot 21.3480(0.0072527 \cdot \Delta H + P_{net})}{(T + 459.7)}$$

Although the form is awkward, it shows the flowmeter/orifice constants.

APPENDIX C

PRELIMINARY TEST DATA

The preliminary data is presented in the tables on the following pages. Six series of tests were run. Each series of tests is described by four tables. The series of data are:

VII. Base line Colorado coal tests (included substoichiometric tests)

VIII. Fineness tests with Colorado coal

IX. Flue gas recirculation for Colorado coal (secondary FGR only)
  A. Base line (no FGR)
  B. FGR

X. Staged combustion tests with Colorado coal
  A. Base line (no staging)
  B. Staged

XI. Slot changes with Colorado coal
  A. Base line (original configuration)
  B. Change #1
  C. Change #2

XII. Burner changes with Colorado coal
  A. Base line (original configuration)
  B. Change #1
  C. Change #2

The table headings are discussed below also:

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Table 1 — Furnace input data in pounds per hour for the natural gas igniter, fuel, primary air (used as transport air for coal only), secondary air, second stage air, and flue gas recycled. (The two numbers for VII-1, fuel are 428/448 and are respectively the fuel weight dry and the fuel weight with normal moisture.)

Table 2 — Total amount of air, in percent of stoichiometric; the heat release rate in 10^3 Btu per cubic foot per hour; the total, averaged gas preheat for all air and any recirculated flue gas; the weight percent of flue gas recycled; and the percent of stoichiometric air which enters through the burner (primary and secondary summed together).

Table 3 — The three NO_x instrument readings in ppm NO reduced to 3% oxygen and dry for the Beckman NDIR, TECo chemiluminescence, and the Whittaker chemical cell; the average of the NDIR and TECo expressed as ppm NO ± the standard deviation of the average; and the conversion of the ppm NO to pounds of NO (not NO_2) per million Btu input as fuel Btu only.

Table 4 — The humidity and barometric pressure in mm Hg; the uncorrected ("raw, as recorded") concentration of oxygen, carbon monoxide, sulfur dioxide, and carbon dioxide; and the ash loadings as weight percent of ash in the flue gas (pounds of ash per hundred pounds of flue gas) and weight percents of carbon and nitrogen as found in the ash (pounds of total carbon and total nitrogen, forms undeterminable, per hundred pounds of ash).

TABLE C.1 SERIES VII – COLORADO COAL, FURNACE DATA (INPUT)

ORIGINAL RUN # AND SERIES OF RUNS	LB. / HR. (DRY WT. / WET WT.) IGNITER (GAS)	FUEL	PRIMARY AIR	SECONDARY AIR	2ND STAGE AIR	FLUE GAS
VII - 1	3.0	428/448	583/644	4153/4509	0/ 0	0
VII - 2	3.0	425/444	590/648	5137/5638	0/ 0	0
VII - 3	2.0	427/448	577/635	3670/4067	0/ 0	0
VII - 4	3.1	261/274	565/609	2510/2709	0/ 0	0
VII - 5	3.1	244/256	573/617	2954/3186	0/ 0	0
VII - 6	3.1	221/232	549/594	1755/1901	0/ 0	0
VII - 7	3.2	573/601	609/650	5867/6269	0/ 0	0
VII - 8	3.1	413/434	613/653	3529/3762	0/ 0	0
VII - 9	3.0	410/430	619/660	3109/3320	0/ 0	0
VII -10	3.1	413/433	628/669	2509/2678	0/ 0	0
VII -11	3.1	414/434	604/643	2355/2514	0/ 0	0
VII -12	3.1	416/437	611/652	2102/2244	0/ 0	0
VII -13	3.1	547/574	674/733	5474/5950	0/ 0	0
VII -14	3.1	527/552	675/742	6538/7173	0/ 0	0
VII -15	3.0	496/520	667/728	4362/4764	0/ 0	0
VII -16	3.0	433/454	589/647	4288/4715	0/ 0	0
VII -17	3.0	416/437	595/651	5159/5649	0/ 0	0
VII -18	3.0	405/425	596/653	3560/3910	0/ 0	0
VII -19	3.1	541/567	674/730	5440/5900	0/ 0	0
VII -20	3.1	546/573	681/722	5443/5794	0/ 0	0
VII -21	3.1	519/545	681/724	6380/6788	0/ 0	0
VII -22	3.1	276/290	518/553	3352/3583	0/ 0	0
VII -23	3.0	266/279	514/550	2507/2684	0/ 0	0
VII -24	3.1	261/274	519/551	2167/2302	0/ 0	0
VII -25	3.0	270/284	520/556	2510/2683	0/ 0	0
VII -26	3.1	452/474	606/646	4397/4685	0/ 0	0
VII -27	3.0	431/452	598/635	5402/5729	0/ 0	0
VII -28	3.1	463/485	674/716	5491/5831	0/ 0	0
VII -29	3.1	426/446	606/644	3756/3994	0/ 0	0

TABLE C.2 SERIES VII – COLORADO COAL, FURNACE DATA (FINAL)

ORIGINAL RUN # AND SERIES OF RUNS	TOTAL AIR, %	HEAT, KBTU/ FT**3 / HR.	GAS PRE-HEAT DEG. F	FLUE GAS RECYCLED TO INPUT (%)	AIR AT BURNER (%)
VII - 1	113.0	49.54	600	0.0	113.0
VII - 2	130.0	50.77	635	0.0	130.0
VII - 3	101.5	48.96	599	0.0	101.5
VII - 4	119.2	30.26	548	0.0	119.2
VII - 5	146.2	29.08	570	0.0	146.2
VII - 6	105.0	25.15	500	0.0	105.0
VII - 7	115.6	66.65	620	0.0	115.6
VII - 8	102.1	47.24	565	0.0	102.1
VII - 9	92.8	46.21	574	0.0	92.8
VII -10	77.4	45.66	542	0.0	77.4
VII -11	72.8	45.66	537	0.0	72.8
VII -12	66.5	45.58	520	0.0	66.5
VII -13	115.0	63.74	622	0.0	115.0
VII -14	140.0	63.19	631	0.0	140.0
VII -15	103.6	56.90	602	0.0	103.6
VII -16	114.9	46.76	296	0.0	114.9
VII -17	141.0	45.66	298	0.0	141.0
VII -18	104.6	43.54	285	0.0	104.6
VII -19	115.6	50.40	286	0.0	115.6
VII -20	115.0	59.10	290	0.0	115.0
VII -21	138.9	56.67	289	0.0	138.9
VII -22	142.0	30.34	285	0.0	142.0
VII -23	115.0	28.09	279	0.0	115.0
VII -24	106.0	28.22	270	0.0	106.0
VII -25	113.6	31.12	556	0.0	113.6
VII -26	113.0	52.42	621	0.0	113.0
VII -27	142.0	51.64	637	0.0	142.0
VII -28	136.0	55.02	633	0.0	136.0
VII -29	104.5	48.89	600	0.0	104.5

TABLE C.3 SERIES VII – COLORADO COAL, NO$_X$ MEASUREMENTS

ORIGINAL SERIES – RUN #-S	PPM NOX 3% O2, DRY NDIR	TECO	WHIT	PPM NOX IN DRY, 3% O2 FLUE GAS	LB. NOX / 10**6 BTU INPUT
VII - 1	951	955	961	953 ± 2	0.96 ± .0
VII - 2	1217	1292	1077	1250 ± 46	1.51 ± .06
VII - 3	641	645	649	643 ± 3	0.59 ± .0
VII - 4	809	832	948	820 ± 17	0.85 ± .02
VII - 5	957	1005	1049	981 ± 34	1.23 ± .04
VII - 6	505	515	595	510 ± 7	0.47 ± .01
VII - 7	1099	1071	1063	1085 ± 20	1.08 ± .02
VII - 8	675	671	691	673 ± 3	0.60 ± .0
VII - 9	532	538	533	535 ± 4	0.44 ± .0
VII -10	208	206	251	207 ± 2	0.14 ± .0
VII -11	109	99	155	104 ± 7	0.07 ± .0
VII -12	81	78	138	79 ± 2	0.05 ± .0
VII -13	1169	1223	1195	1196 ± 38	1.21 ± .04
VII -14	1324	1411	1380	1368 ± 62	1.67 ± .08
VII -15	843	847	958	845 ± 3	0.78 ± .0
VII -16	937	897	859	917 ± 28	0.94 ± .03
VII -17	1132	1072	1050	1102 ± 43	1.35 ± .35
VII -18	589	565	591	577 ± 17	0.54 ± .02
VII -19	952	938	991	945 ± 10	0.96 ± .01
VII -20	861	963	922	912 ± 72	0.90 ± .07
VII -21	966	1118	1033	1042 ± 107	1.23 ± .13
VII -22	809	900	847	854 ± 65	1.03 ± .08
VII -23	665	649	671	657 ± 11	0.65 ± .01
VII -24	450	435	470	443 ± 11	0.40 ± .01
VII -25	762	787	806	774 ± 18	0.76 ± .02
VII -26	1050	1077	1119	1064 ± 19	1.04 ± .02
VII -27	1299	1356	1375	1327 ± 41	1.49 ± .05
VII -28	1307	1303	1363	1305 ± 3	1.51 ± .0
VII -29	869	856	923	862 ± 9	0.78 ± .01

TABLE C.4 SERIES VII – COLORADO COAL, OTHER MEASUREMENTS

ORIGINAL SERIES – RUN #-S	HUM. (MM WET)	BAR. (MM WET)	O2 %	PPM CO	PPM SO2	CO2 %	ASH %	C IN ASH %	N IN ASH %
VII - 1	13.1	726	2.7	90	550	----	0.39	28.0	----
VII - 2	11.8	725	5.8	60	500	----	----	----	----
VII - 3	12.4	724	0.5	1500	600	----	0.36	43.2	----
VII - 4	7.4	733	3.4	40	650	----	----	----	----
VII - 5	7.3	733	6.6	40	500	----	0.40	3.8	----
VII - 6	8.1	727	1.1	850	575	----	----	----	----
VII - 7	5.8	735	3.1	120	550	----	----	----	----
VII - 8	5.2	735	0.6	3000	600	----	----	----	----
VII - 9	5.5	735	0.7	34490	620	----	----	----	----
VII -10	5.4	735	0.0	95427	580	----	0.80	50.2	----
VII -11	5.4	735	0.0	145000	450	----	0.85	52.1	----
VII -12	5.4	735	0.0	205000	480	----	----	----	----
VII -13	9.4	733	3.0	70	660	----	----	----	----
VII -14	12.0	732	6.0	60	575	----	----	----	----
VII -15	10.3	732	0.9	2600	675	----	0.92	-??-	----
VII -16	11.9	737	3.0	150	325	----	----	----	----
VII -17	10.9	737	6.1	60	290	----	----	----	----
VII -18	11.5	737	1.1	2600	375	----	----	----	----
VII -19	8.8	738	3.1	240	450	----	----	----	----
VII -20	4.4	729	3.0	115	425	----	----	----	----
VII -21	5.0	729	5.9	115	400	----	----	----	----
VII -22	5.6	730	6.2	60	380	----	----	----	----
VII -23	5.9	731	3.0	40	200	----	----	----	----
VII -24	4.6	730	0.9	930	500	----	----	----	----
VII -25	5.6	730	2.9	375	375	----	----	----	----
VII -26	5.2	730	2.7	100	310	----	----	----	----
VII -27	4.6	730	6.2	100	300	----	----	----	----
VII -28	4.8	731	5.4	150	300	----	----	----	----
VII -29	4.8	730	1.0	950	400	----	----	----	----

TABLE C.5 SERIES VIII – FINENESS – COLORADO COAL, FURNACE DATA (INPUT)

ORIGINAL RUN # AND SERIES OF RUNS	LB. / HR. (DRY WT. / WET WT.)					
	IGNITER (GAS)	FUEL	PRIMARY AIR	SECONDARY AIR	2ND STAGE AIR	FLUE GAS
VIII- 1	3.3	454/476	622/659	4499/4773	0/ 0	0
VIII- 2	3.2	456/478	616/651	4464/4722	0/ 0	0
VIII- 3	3.4	442/464	629/666	5852/6188	0/ 0	0
VIII- 4	3.4	435/456	637/674	3752/3972	0/ 0	0
VIII- 5	3.4	282/296	585/620	2600/2758	0/ 0	0
VIII- 6	3.2	273/286	575/610	2197/2333	0/ 0	0
VIII- 7	3.2	276/289	575/610	3524/3740	0/ 0	0
VIII- 8	3.2	451/473	617/655	4469/4743	0/ 0	0
VIII- 9	3.2	456/479	617/656	5827/6191	0/ 0	0
VIII- 10	3.2	429/450	626/674	4417/4732	0/ 0	1290
VIII- 11	3.2	530/556	664/713	5400/5787	0/ 0	0
VIII- 12	3.2	439/461	613/659	4368/4697	0/ 0	0
VIII- 13	3.2	450/472	613/653	5781/6069	0/ 0	0
VIII- 14	3.2	410/430	621/664	3510/3761	0/ 0	0

TABLE C.6 SERIES VIII – FINENESS – COLORADO COAL, FURNACE DATA (FINAL)

ORIGINAL RUN # AND SERIES OF RUNS	TOTAL AIR, %	HEAT, KBTU/ FT**3 / HR.	GAS PRE-HEAT DEG. F	FLUE GAS RECYCLED TO INPUT (%)	AIR AT BURNER (%)
VIII- 1	115.0	52.97	618	0.0	115.0
VIII- 2	113.7	52.97	615	0.0	113.7
VIII- 3	149.4	53.44	633	0.0	149.4
VIII- 4	102.8	49.41	592	0.0	102.8
VIII- 5	114.3	32.56	551	0.0	114.3
VIII- 6	102.9	31.04	530	0.0	102.9
VIII- 7	150.5	33.09	583	0.0	150.5
VIII- 8	114.9	52.50	618	0.0	114.9
VIII- 9	144.1	54.86	629	0.0	144.1
VIII- 10	119.9	51.64	621	22.2	119.9
VIII- 11	117.0	61.70	620	0.0	117.0
VIII- 12	115.6	47.63	293	0.0	115.6
VIII- 13	143.0	49.20	282	0.0	143.0
VIII- 14	102.7	44.01	270	0.0	102.7

TABLE C.7 SERIES VIII – FINENESS – COLORADO COAL, NO$_X$ MEASUREMENTS

ORIGINAL SERIES - RUN #-S	PPM NOX 3% O2, DRY			PPM NOX IN DRY, 3% O2 FLUE GAS	LB. NOX / 10**6 BTU INPUT
	NDIR	TECO	WHIT		
VIII- 1	1002	1095	1057	1044 ± 58	1.03 ± .06
VIII- 2	1096	1091	1084	1094 ± 4	1.07 ± .0
VIII- 3	1292	1326	1297	1309 ± 24	1.44 ± .03
VIII- 4	738	716	723	727 ± 16	0.65 ± .01
VIII- 5	796	776	783	786 ± 14	0.77 ± .01
VIII- 6	552	527	561	539 ± 18	0.48 ± .02
VIII- 7	1192	1134	1151	1163 ± 13	1.45 ± .02
VIII- 8	1058	1115	1090	1086 ± 41	1.07 ± .04
VIII- 9	1248	1390	1258	1299 ± 72	1.58 ± .09
VIII- 10	985	939	924	962 ± 33	1.00 ± .03
VIII- 11	1224	1227	1155	1226 ± 2	1.24 ± .0
VIII- 12	861	851	953	956 ± 7	0.86 ± .01
VIII- 13	1011	1018	1007	1014 ± 5	1.23 ± .01
VIII- 14	631	604	621	617 ± 19	0.55 ± .02

TABLE C.8 SERIES VIII – FINENESS – COLORADO COAL, OTHER MEASUREMENTS

ORIGINAL SERIES - RUN #-S	HUM. (MM WET)	BAR. (MM WET)	O2 %	PPM CO	PPM SO2	CO2 %	ASH %	C IN ASH %	N IN ASH %
VIII- 1	4.6	737	3.0	80	67	----	0.45	13.3	----
VIII- 2	4.1	739	2.8	100	675	----	----	----	----
VIII- 3	4.3	761	6.9	80	540	----	----	----	----
VIII- 4	4.3	761	0.7	2150	790	----	----	----	----
VIII- 5	4.6	760	2.9	150	650	----	----	----	----
VIII- 6	4.6	735	0.7	1700	700	----	----	----	----
VIII- 7	4.6	735	7.0	100	525	----	----	----	----
VIII- 8	4.6	733	3.0	150	700	----	----	----	----
VIII- 9	4.9	733	6.4	8	510	----	----	----	----
VIII- 10	6.3	733	3.7	90	640	----	----	----	----
VIII- 11	6.3	732	3.3	100	700	----	0.45	3.3	----
VIII- 12	6.8	732	3.1	105	1125	----	----	----	----
VIII- 13	5.1	731	6.3	90	900	----	----	----	----
VIII- 14	6.1	731	0.6	475	1250	----	0.65	31.5	----

TABLE C.9 SERIES IX – F. G. R. COLORADO COAL, FURNACE DATA (INPUT)

ORIGINAL RUN # AND SERIES OF RUNS	LB. / HR. (DRY WT. / WET WT.)					
	IGNITER (GAS)	FUEL	PRIMARY AIR	SECONDARY AIR	2ND STAGE AIR	FLUE GAS
IX A - 1	3.1	454/476	605/640	4394/4706	0/ 0	0
IX A - 2	2.9	317/332	518/551	3096/3283	0/ 0	0
IX B - 3	3.1	456/478	598/638	4396/4690	0/ 0	382
IX B - 4	3.1	452/474	598/636	4289/4563	0/ 0	1052
IX B - 5	3.1	326/342	514/562	3134/3424	0/ 0	985

TABLE C.10 SERIES IX – F. G. R. COLORADO COAL, FURNACE DATA (FINAL)

ORIGINAL RUN # AND SERIES OF RUNS	TOTAL AIR, %	HEAT, KBTU/ FT**3 / HR.	GAS PRE-HEAT DEG. F	FLUE GAS RECYCLED TO INPUT (%)	AIR AT BURNER (%)
IX A - 1	112.4	52.58	619	0.0	112.4
IX A - 2	115.7	36.63	586	0.0	115.7
IX B - 3	111.9	53.21	619	6.6	111.9
IX B - 4	110.4	53.28	616	19.5	110.4
IX B - 5	113.7	38.90	588	22.7	113.7

TABLE C.11 SERIES IX – F. G. R. COLORADO COAL, NO$_X$ MEASUREMENTS

ORIGINAL SERIES - RUN #-S	PPM NOX 3% O2, DRY			PPM NOX IN DRY, 3% O2 FLUE GAS	LB. NOX / 10**6 BTU INPUT
	NDIR	TECO	WHIT		
IX A - 1	1010	1027	856	1018 ± 12	0.99 ± .01
IX A - 2	806	816	726	811 ± 7	0.81 ± .01
IX B - 3	960	976	868	968 ± 11	0.94 ± .01
IX B - 4	868	938	780	888 ± 25	0.85 ± .03
IX B - 5	762	778	654	770 ± 11	0.77 ± .01

TABLE C.12 SERIES IX – F. G. R. COLORADO COAL, OTHER MEASUREMENTS

ORIGINAL SERIES - RUN #-S	HUM. (MM WET)	BAR. (MM WET)	O2 %	PPM CO	PPM SO2	CO2 %	ASH %	C IN ASH %	N IN ASH %
IX A - 1	6.2	737	2.6	120	500	----	----	----	----
IX A - 2	4.9	737	3.1	30	550	----	----	----	----
IX B - 3	5.5	737	2.5	240	400	----	----	----	----
IX B - 4	5.0	737	2.2	130	590	----	----	----	----
IX B - 5	10.3	737	2.8	30	550	----	----	----	----

TABLE C.13 SERIES X – STAGING COLORADO COAL, FURNACE DATA (INPUT)

ORIGINAL RUN # AND SERIES OF RUNS	LB. / HR. (DRY WT. / WET WT.)					
	IGNITER (GAS)	FUEL	PRIMARY AIR	SECONDARY AIR	2ND STAGE AIR	FLUE GAS
X A - 1	3.2	301/314	520/560	2593/2707	0/ 0	0
X A - 2	3.2	332/348	516/565	3269/3468	0/ 0	0
X A - 3	3.1	330/346	518/555	3238/3495	0/ 0	0
X A - 4	2.9	310/325	520/567	3542/3804	0/ 0	0
X A - 5	3.1	329/349	522/556	4281/4963	0/ 0	0
X A - 6	3.1	453/475	610/655	4375/4692	0/ 0	0
X A - 7	3.1	447/469	609/655	4375/4711	0/ 0	0
X A - 8	3.1	442/464	607/651	4345/4660	0/ 0	0
X A - 9	2.7	443/469	596/652	4309/4715	0/ 0	0
X A - 10	3.1	440/462	595/637	4369/4683	0/ 0	0
X A - 11	3.2	439/461	590/651	4335/4787	0/ 0	0
X A - 12	3.2	451/473	596/658	4882/5397	0/ 0	0
X A - 13	3.2	456/478	578/641	5464/6058	0/ 0	0
X A - 14	2.6	429/450	602/657	4339/4733	0/ 0	0
X A - 15	3.2	448/468	600/655	4389/4742	0/ 0	0
X A - 16	2.9	444/466	606/652	4337/4668	0/ 0	0
X A - 17	2.6	446/466	597/649	5713/6215	0/ 0	0
X A - 18	2.9	445/466	602/648	5913/6236	0/ 0	0
X A - 19	2.8	462/510	596/652	4908/5388	0/ 0	0
X A - 20	2.9	405/423	598/658	3562/3908	0/ 0	0
X A - 21	2.9	520/546	669/728	5394/5906	0/ 0	0
X A - 22	3.1	439/463	600/655	4345/4735	0/ 0	0
X A - 23	3.1	314/329	515/553	3916/4197	0/ 0	0
X A - 24	3.1	403/423	607/651	3687/3767	0/ 0	0
X B - 25	3.2	300/315	519/561	1805/1915	747/ 792	0
X B - 26	3.1	334/350	533/566	2568/2720	667/ 718	0
X B - 27	3.1	321/337	522/556	1619/1726	1487/1557	0
X B - 28	3.1	338/355	522/556	3391/3606	881/ 936	0
X B - 29	3.1	351/368	522/557	2521/2640	1786/1908	0
X B - 30	3.1	452/474	614/650	4016/4315	467/ 502	0
X B - 31	3.1	443/464	606/669	3457/3609	426/ 457	0
X B - 32	3.1	477/500	604/667	2766/2956	1829/1954	0
X B - 33	3.1	439/463	630/684	2088/2275	2314/2529	0
X B - 34	2.9	435/456	615/660	1709/1831	2781/2988	0
X B - 35	3.1	431/452	528/563	3696/3877	967/1047	0
X B - 36	3.2	429/450	588/662	2375/2626	1805/1999	0
X B - 37	2.6	416/436	547/652	1783/1940	2613/2836	0
X B - 38	2.6	428/449	589/650	1312/1426	2797/3065	0
X B - 39	2.7	420/440	614/658	3891/4177	453/ 486	0
X B - 40	3.1	370/387	588/665	3393/3659	932/1006	0
X B - 41	3.1	399/418	597/653	2469/2701	1879/2050	0
X B - 42	3.1	410/430	598/646	2079/2244	2301/2491	0
X B - 43	2.9	404/423	590/636	1636/1758	2869/3093	0
X B - 44	2.7	430/451	603/671	3556/3850	920/1026	0
X B - 45	2.8	428/448	602/646	3867/4124	1855/1993	0
X B - 46	2.7	450/481	605/658	4173/4533	1503/1636	0
X B - 47	2.8	429/449	612/663	2339/2525	3456/3746	0
X B - 48	2.9	401/420	591/649	2561/2813	976/1073	0
X B - 49	2.9	397/416	587/643	1495/1637	1963/2155	0
X B - 50	2.9	528/554	667/728	4224/4612	1148/1257	0
X B - 51	2.9	510/541	660/722	2998/3274	2346/2571	0
X B - 52	3.1	424/445	593/638	3066/3296	1283/1381	0
X B - 53	2.9	421/442	602/647	1832/1967	2354/2531	0
X B - 54	3.1	407/427	610/652	2978/3186	1159/1240	0
X B - 55	2.9	419/440	603/667	1989/2137	2290/2463	0
X B - 56	2.9	309/324	525/561	2156/2303	1796/1919	0
X B - 57	3.1	400/419	594/637	1246/1334	2249/2433	0

TABLE C.14 SERIES X – STAGING COLORADO COAL, FURNACE DATA (FINAL)

ORIGINAL RUN # AND SERIES OF RUNS	TOTAL AIR, %	HEAT, KBTU/FT**3 / HR.	GAS PRE-HEAT DEG. F	FLUE GAS RECYCLED TO INPUT (%)	AIR AT BURNER (%)
X A - 1	103.9	34.35	555	0.0	107.0
X A - 2	116.3	38.43	580	0.0	116.3
X A - 3	115.7	38.20	593	0.0	115.7
X A - 4	133.7	36.03	606	0.0	133.2
X A - 5	140.3	39.61	620	0.0	140.3
X A - 6	112.3	52.42	610	0.0	112.3
X A - 7	113.7	51.95	615	0.0	113.7
X A - 8	114.3	50.93	596	0.0	114.3
X A - 9	113.0	51.17	597	0.0	113.0
X A - 10	115.0	50.93	590	0.0	115.0
X A - 11	114.3	51.32	619	0.0	114.3
X A - 12	123.0	53.37	630	0.0	123.0
X A - 13	135.1	54.62	641	0.0	135.1
X A - 14	117.7	49.90	623	0.0	117.7
X A - 15	114.3	51.72	603	0.0	114.3
X A - 16	113.7	51.48	622	0.0	113.7
X A - 17	145.1	52.89	607	0.0	145.1
X A - 18	147.2	52.82	587	0.0	147.2
X A - 19	114.3	57.30	630	0.0	114.3
X A - 20	106.8	46.21	596	0.0	106.9
X A - 21	119.2	60.99	634	0.0	119.2
X A - 22	115.0	67.47	286	0.0	115.0
X A - 23	144.1	34.47	290	0.0	144.1
X A - 24	103.6	43.38	275	0.0	105.4
X B - 25	103.7	33.17	537	0.0	78.4
X B - 26	115.6	37.97	574	0.0	94.3
X B - 27	115.0	34.82	583	0.0	67.7
X B - 28	144.0	39.06	606	0.0	117.2
X B - 29	130.9	39.30	632	0.0	88.1
X B - 30	114.9	51.77	593	0.0	104.4
X B - 31	114.9	49.91	596	0.0	93.6
X B - 32	111.3	52.50	620	0.0	72.1
X B - 33	116.2	47.63	629	0.0	62.4
X B - 34	114.7	46.61	639	0.0	96.4
X B - 35	119.1	48.96	621	0.0	96.9
X B - 36	115.6	47.16	636	0.0	70.6
X B - 37	117.7	44.72	629	0.0	58.6
X B - 38	112.3	45.27	634	0.0	65.5
X B - 39	120.6	48.10	603	0.0	109.0
X B - 40	132.3	43.07	585	0.0	107.3
X B - 41	120.2	43.93	600	0.0	78.3
X B - 42	123.8	44.48	606	0.0	66.5
X B - 43	120.7	43.15	611	0.0	56.2
X B - 44	120.6	48.89	592	0.0	98.7
X B - 45	130.5	48.41	589	0.0	106.2
X B - 46	140.0	52.03	591	0.0	108.6
X B - 47	152.0	46.53	606	0.0	70.2
X B - 48	105.1	44.41	588	0.0	80.2
X B - 49	104.0	42.36	604	0.0	53.5
X B - 50	117.0	59.73	627	0.0	94.7
X B - 51	119.1	56.75	664	0.0	72.5
X B - 52	118.8	45.27	276	0.0	87.9
X B - 53	115.9	46.33	279	0.0	50.9
X B - 54	110.9	43.46	281	0.0	89.8
X B - 55	110.8	44.17	279	0.0	63.0
X B - 56	147.2	52.93	283	0.0	88.1
X B - 57	104.7	41.89	273	0.0	66.9

TABLE C.15 SERIES X – STAGING COLORADO COAL, NO$_X$ MEASUREMENTS

ORIGINAL SERIES - RUN 0-5	PPM NOX 3% O2, DRY			PPM NOX IN DRY, 3% O2 FLUE GAS	LB. NOX / 10**6 BTU INPUT
	MDIR	TECO	WHIT		
X A - 1	562	574	662	569 ± 9	0.51 ± .01
X A - 2	891	963	891	917 ± 37	0.91 ± .04
X A - 3	851	897	726	869 ± 26	0.87 ± .03
X A - 4	1020	1097	969	1057 ± 42	1.23 ± .05
X A - 5	1162	1293	1056	1207 ± 69	1.32 ± .08
X A - 6	955	1016	865	986 ± 43	0.96 ± .04
X A - 7	907	993	828	990 ± 5	0.98 ± .0
X A - 8	962	968	833	965 ± 4	0.96 ± .0
X A - 9	1041	1072	886	1056 ± 23	1.06 ± .02
X A - 10	1128	1141	931	1135 ± 9	1.13 ± .01
X A - 11	1052	1086	810	1069 ± 23	1.09 ± .02
X A - 12	1220	1277	1075	1248 ± 40	1.37 ± .04
X A - 13	1340	1443	1103	1391 ± 73	1.44 ± .08
X A - 14	1118	1141	967	1129 ± 16	1.17 ± .02
X A - 15	1057	1144	933	1121 ± 34	1.12 ± .03
X A - 16	1021	1048	910	1035 ± 19	1.02 ± .02
X A - 17	1313	1418	1170	1366 ± 74	1.71 ± .09
X A - 18	1388	1404	1200	1396 ± 11	1.75 ± .01
X A - 19	1027	1049	993	1038 ± 16	1.09 ± .02
X A - 20	672	686	556	679 ± 10	0.64 ± .01
X A - 21	1167	1156	1068	1192 ± 23	1.24 ± .02
X A - 22	956	892	709	874 ± 76	0.88 ± .03
X A - 23	856	930	790	897 ± 6	1.10 ± .0
X A - 24	425	405	401	415 ± 14	0.39 ± .01
X B - 25	256	248	256	252 ± 5	0.21 ± .0
X B - 26	567	576	690	571 ± 6	0.57 ± .01
X B - 27	287	289	219	288 ± 1	0.29 ± .0
X B - 28	975	1006	881	990 ± 22	1.21 ± .03
X B - 29	580	584	521	582 ± 3	0.69 ± .0
X B - 30	927	963	853	954 ± 40	0.93 ± .04
X B - 31	735	786	698	761 ± 36	0.76 ± .04
X B - 32	390	407	350	398 ± 12	0.38 ± .01
X B - 33	387	384	325	386 ± 2	0.39 ± .0
X B - 34	393	385	334	389 ± 6	0.40 ± .01
X B - 35	750	819	672	786 ± 49	0.83 ± .05
X B - 36	373	451	339	412 ± 55	0.42 ± .06
X B - 37	386	384	336	385 ± 2	0.40 ± .0
X B - 38	330	327	286	329 ± 2	0.32 ± .0
X B - 39	885	912	779	899 ± 19	0.94 ± .02
X B - 40	878	910	774	898 ± 29	1.03 ± .03
X B - 41	638	664	508	651 ± 19	0.72 ± .02
X B - 42	[illegible]	549	469	539 ± 14	0.58 ± .02
X B - 43	[illegible]	918	429	905 ± 18	0.90 ± .02
X B - 44	[illegible]	753	637	768 ± 7	0.81 ± .01
X B - 45	1036	1043	925	1039 ± 5	1.33 ± .01
X B - 46	967	992	846	979 ± 17	1.19 ± .02
X B - 47	749	793	669	771 ± 31	1.01 ± .04
X B - 48	328	335	320	331 ± 5	0.31 ± .0
X B - 49	311	313	293	312 ± 2	0.29 ± .0
X B - 50	758	768	676	763 ± 7	0.79 ± .01
X B - 51	490	503	441	496 ± 10	0.52 ± .01
X B - 52	431	434	383	433 ± 2	0.45 ± .0
X B - 53	396	394	356	395 ± 2	0.40 ± .0
X B - 54	499	486	444	493 ± 9	0.51 ± .01
X B - 55	483	471	427	477 ± 9	0.49 ± .01
X B - 56	482	472	429	477 ± 7	0.60 ± .01
X B - 57	248	242	242	245 ± 19	0.23 ± .02

TABLE C.16 SERIES X – STAGING COLORADO COAL, OTHER MEASUREMENTS

ORIGINAL SERIES - RUN 0-5	HUM. (MM WET)	BAR. (MM WET)	O2 %	PPM CO	PPM SO2	CO2 %	ASH %	C IN ASH %	N IN ASH %
X A - 1	4.3	734	0.9	1700	525	----	----	----	----
X A - 2	3.6	735	3.2	130	430	----	----	----	----
X A - 3	5.5	742	3.1	30	500	----	----	----	----
X A - 4	9.9	733	5.1	100	600	----	----	----	----
X A - 5	9.3	742	6.0	100	400	----	0.20	18.1	-??-
X A - 6	6.4	730	2.4	325	500	----	0.78	26.1	-??-
X A - 7	7.3	738	2.0	60	600	----	----	----	----
X A - 8	6.5	740	2.9	150	620	----	----	----	----
X A - 9	10.0	738	2.7	120	700	----	----	----	----
X A - 10	6.4	742	3.0	90	700	----	----	----	----
X A - 11	13.2	737	2.9	100	610	----	----	----	----
X A - 12	13.6	736	4.2	70	570	----	----	----	----
X A - 13	14.7	736	5.5	75	675	----	----	----	----
X A - 14	10.3	740	3.4	100	550	----	----	----	----
X A - 15	8.0	737	2.9	150	600	----	----	----	----
X A - 16	7.1	738	2.8	120	570	----	----	----	----
X A - 17	9.6	738	6.5	60	620	----	----	----	----
X A - 18	6.6	742	6.7	60	575	----	----	----	----
X A - 19	11.4	728	2.9	180	700	----	----	----	----
X A - 20	12.1	729	1.1	1600	690	----	----	----	----
X A - 21	10.8	730	3.6	120	650	----	----	----	----
X A - 22	9.6	728	3.0	130	600	----	0.69	15.6	-??-
X A - 23	5.3	736	6.4	30	650	----	----	----	----
X A - 24	6.6	730	1.2	9500	575	----	----	----	----
X B - 25	4.4	734	1.4	12500	510	----	----	----	----
X B - 26	4.2	735	3.1	300	410	----	0.61	-??-	-??-
X B - 27	5.3	742	3.1	1900	490	----	----	----	----
X B - 28	5.5	742	6.4	100	375	----	----	----	----
X B - 29	5.7	742	6.3	100	390	----	----	----	----
X B - 30	6.8	731	3.0	190	500	----	----	----	----
X B - 31	5.9	731	3.0	150	500	----	----	----	----
X B - 32	5.9	732	2.4	360	500	----	0.91	39.0	-??-
X B - 33	10.4	738	3.7	360	575	----	----	----	----
X B - 34	6.8	738	3.7	910	525	----	----	----	----
X B - 35	14.4	735	5.6	180	500	----	----	----	----
X B - 36	13.9	735	2.8	360	600	----	----	----	----
X B - 37	10.1	740	3.4	210	550	----	----	----	----
X B - 38	9.6	740	2.6	360	520	----	----	----	----
X B - 39	6.6	738	3.8	210	525	----	----	----	----
X B - 40	7.5	739	5.7	30	623	----	0.90	20.9	-??-
X B - 41	11.2	739	4.9	60	600	----	----	----	----
X B - 42	8.2	739	4.2	90	600	----	0.94	17.9	-??-
X B - 43	7.5	739	4.8	150	550	----	0.91	23.3	-??-
X B - 44	15.6	740	3.8	240	500	----	----	----	----
X B - 45	6.6	742	7.0	60	500	----	0.45	9.1	-??-
X B - 46	9.4	738	6.0	60	550	----	----	----	----
X B - 47	8.7	742	7.2	60	550	----	0.44	8.2	-??-
X B - 48	11.6	729	1.3	6400	640	----	1.03	35.1	-??-
X B - 49	11.3	729	1.0	3100	700	----	----	----	----
X B - 50	10.5	731	3.3	150	625	----	----	----	----
X B - 51	11.0	730	3.6	340	625	----	----	----	----
X B - 52	6.8	728	3.6	1200	450	----	----	----	----
X B - 53	6.7	729	3.2	1200	650	----	0.99	33.4	-??-
X B - 54	5.8	729	3.6	1100	690	----	----	----	----
X B - 55	6.9	729	5.6	1100	500	----	0.81	29.0	-??-
X B - 56	5.7	737	6.7	150	450	----	----	----	----
X B - 57	6.2	730	1.7	4000	575	----	----	----	----

TABLE C.17 SERIES XI – SLOT CHANGES, FURNACE DATA (INPUT)

ORIGINAL RUN # AND SERIES OF RUNS	LB. / HR. (DRY WT. / WET WT.)					
	IGNITER (GAS)	FUEL	PRIMARY AIR	SECONDARY AIR	2ND STAGE AIR	FLUE GAS
XI A - 1	2.9	423/466	578/653	4220/4770	0/ 0	0
XI A - 2	3.7	492/516	641/723	3771/4251	1119/1264	0
XI A - 3	2.9	422/465	595/661	2009/2264	2267/2541	0
XI A - 4	2.9	429/450	596/662	3076/3479	1119/1267	0
XI A - 5	2.9	440/461	599/660	2069/2342	2273/2577	0
XI A - 6	2.9	423/465	580/655	3734/4187	0/ 0	0
XI A - 7	2.9	421/461	587/665	2523/2852	1174/1329	0
XI A - 8	2.9	406/426	579/656	1391/1573	2269/2551	0
XI A - 9	2.9	369/397	181/207	2423/2739	1169/1323	0
XI A -10	2.9	414/436	574/655	1421/1603	2225/2517	0
XI A -11	2.9	304/324	499/566	3022/3407	0/ 0	0
XI A -12	2.9	305/319	499/564	1960/2221	1030/1169	0
XI A -13	2.9	288/302	498/562	738/ 830	2021/2278	0
XI A -14	2.9	310/325	498/562	993/1117	2013/2259	0
XI B - 1	3.0	435/456	597/656	4261/4765	0/ 0	0
XI B - 2	3.0	432/454	596/655	3159/3549	1157/1302	0
XI B - 3	3.0	419/439	576/647	1798/2016	2290/2572	0
XI B - 4	3.0	454/476	593/662	3200/3594	1209/1356	0
XI B - 5	2.9	440/462	183/206	2639/2966	2195/2466	0
XI B - 6	2.9	419/440	580/649	3707/4151	0/ 0	0
XI B - 7	2.9	399/417	572/643	2417/2719	1069/1203	0
XI B - 8	2.9	387/406	564/635	1334/1497	2069/2329	0
XI B - 9	2.9	420/448	582/652	2658/2980	1040/1167	0
XI B -10	2.9	423/444	583/656	1736/1946	1992/2239	0
XI B -11	2.9	313/329	502/561	3012/3375	0/ 0	0
XI B -12	2.9	301/316	510/569	1997/2240	404/ 458	0
XI B -13	3.0	299/313	504/563	1186/1320	1730/1932	0
XI B -14	3.0	298/313	504/562	1180/1315	1774/1990	0
XI C - 1	3.1	419/440	594/652	4405/4935	0/ 0	0
XI C - 2	3.0	436/457	586/662	1138/1446	1157/1272	0
XI C - 3	3.0	430/451	592/657	1949/2142	2267/2499	0
XI C - 4	3.0	431/452	600/655	3170/3406	1179/1288	0
XI C - 5	3.0	437/458	594/650	2094/2279	2240/2456	0
XI C - 6	3.0	432/453	607/665	3786/4154	0/ 0	0
XI C - 7	3.0	419/439	589/647	2521/2770	1145/1260	0
XI C - 8	3.0	419/439	599/665	1445/1580	2246/2462	0
XI C - 9	3.0	394/413	592/649	2141/2350	1165/1280	0
XI C -10	3.0	431/452	596/660	1433/1568	2240/2468	0
XI C -11	3.0	319/335	510/558	3060/3352	0/ 0	0
XI C -12	3.0	303/318	501/550	1863/2047	1060/1165	0
XI C -13	3.0	308/323	509/562	951/1047	1985/2191	0
XI C -14	3.0	320/335	519/569	1027/1126	2049/2252	0

TABLE C.18 SERIES XI – SLOT CHANGES, FURNACE DATA (FINAL)

ORIGINAL RUN # AND SERIES OF RUNS	TOTAL AIR, %	HEAT, KBTU/ FT**3 / HR.	GAS PRE-HEAT DEG. F	FLUE GAS RECYCLED TO INPUT (%)	AIR AT BURNER (%)
XI A - 1	115.6	49.44	618	0.0	115.6
XI A - 2	114.6	56.59	584	0.0	91.4
XI A - 3	117.0	45.74	628	0.0	62.6
XI A - 4	113.6	48.02	605	0.0	67.0
XI A - 5	114.3	47.59	618	0.0	61.6
XI A - 6	102.9	48.65	594	0.0	102.9
XI A - 7	103.9	46.49	593	0.0	79.6
XI A - 8	104.4	43.07	605	0.0	49.6
XI A - 9	104.2	40.95	640	0.0	71.9
XI A -10	104.2	44.01	607	0.0	49.3
XI A -11	115.0	36.09	588	0.0	115.0
XI A -12	116.3	33.80	587	0.0	91.9
XI A -13	115.0	30.26	605	0.0	45.6
XI A -14	115.6	32.77	594	0.0	49.8
XI B - 1	113.7	51.01	649	0.0	113.7
XI B - 2	115.6	48.49	609	0.0	88.3
XI B - 3	114.0	44.96	620	0.0	54.0
XI B - 4	112.3	50.77	616	0.0	49.2
XI B - 5	115.6	48.10	661	0.0	69.0
XI B - 6	104.3	48.02	595	0.0	104.3
XI B - 7	104.0	43.93	594	0.0	74.6
XI B - 8	104.4	41.18	605	0.0	49.9
XI B - 9	102.1	47.31	601	0.0	77.3
XI B -10	104.0	45.39	606	0.0	55.9
XI B -11	114.0	36.31	591	0.0	114.0
XI B -12	114.3	33.56	592	0.0	94.5
XI B -13	116.3	31.91	590	0.0	57.4
XI B -14	116.3	31.91	580	0.0	57.3
XI C - 1	116.3	51.32	616	0.0	116.3
XI C - 2	114.2	48.65	598	0.0	47.1
XI C - 3	114.1	46.45	628	0.0	60.2
XI C - 4	115.9	48.18	604	0.0	88.0
XI C - 5	114.9	47.31	630	0.0	62.5
XI C - 6	103.8	49.59	605	0.0	103.9
XI C - 7	103.7	46.29	608	0.0	79.7
XI C - 8	104.3	44.56	615	0.0	49.5
XI C - 9	100.8	43.23	603	0.0	70.7
XI C -10	101.1	45.82	623	0.0	47.7
XI C -11	113.6	37.02	595	0.0	113.6
XI C -12	114.7	33.96	593	0.0	79.2
XI C -13	113.5	32.62	613	0.0	48.1
XI C -14	114.3	33.47	610	0.0	49.1

TABLE C.19 SERIES XI – SLOT CHANGES, NO$_X$ MEASUREMENTS

ORIGINAL SERIES - RUN #-S	PPM NOX 3% O2, DRY			PPM NOX IN DRY, 3% O2 FLUE GAS	LB. NOX / 10**6 BTU INPUT
	NDIR	TECO	WHIT		
XI A - 1	1064	1153	1394	1108 ± 63	1.17 ± .07
XI A - 2	864	905	1110	885 ± 29	0.92 ± .03
XI A - 3	402	426	484	414 ± 17	0.44 ± .02
XI A - 4	722	767	829	745 ± 32	0.77 ± .03
XI A - 5	536	565	628	551 ± 20	0.58 ± .02
XI A - 6	743	771	915	757 ± 20	0.72 ± .02
XI A - 7	459	475	559	467 ± 12	0.45 ± .01
XI A - 8	309	321	361	315 ± 9	0.31 ± .01
XI A - 9	379	398	464	389 ± 13	0.37 ± .01
XI A -10	307	323	362	315 ± 11	0.30 ± .01
XI A -11	967	1015	1098	991 ± 48	1.03 ± .05
XI A -12	545	570	649	557 ± 17	0.59 ± .02
XI A -13	284	292	314	288 ± 6	0.30 ± .01
XI A -14	374	350	385	362 ± 11	0.36 ± .01
XI B - 1	1061	1106	1384	1083 ± 30	1.11 ± .03
XI B - 2	821	847	869	834 ± 19	0.87 ± .02
XI B - 3	405	423	457	414 ± 13	0.43 ± .01
XI B - 4	690	719	792	704 ± 21	0.72 ± .02
XI B - 5	562	587	642	574 ± 17	0.59 ± .02
XI B - 6	777	814	932	796 ± 26	0.76 ± .02
XI B - 7	423	444	477	434 ± 15	0.41 ± .01
XI B - 8	394	405	424	399 ± 9	0.38 ± .01
XI B - 9	393	409	487	401 ± 11	0.37 ± .01
XI B -10	315	322	367	318 ± 5	0.30 ± .0
XI B -11	849	865	893	857 ± 11	0.88 ± .01
XI B -12	596	605	650	601 ± 5	0.62 ± .01
XI B -13	443	426	459	434 ± 12	0.45 ± .01
XI B -14	367	356	383	360 ± 9	0.38 ± .01
XI C - 1	1065	1128	1105	1096 ± 45	1.13 ± .05
XI C - 2	626	721	707	673 ± 67	0.68 ± .07
XI C - 3	290	299	324	295 ± 6	0.30 ± .01
XI C - 4	599	624	677	611 ± 17	0.63 ± .02
XI C - 5	506	522	541	513 ± 11	0.52 ± .01
XI C - 6	772	796	927	784 ± 16	0.73 ± .02
XI C - 7	332	343	383	338 ± 8	0.31 ± .01
XI C - 8	199	200	221	199 ± 1	0.19 ± .0
XI C - 9	388	382	395	385 ± 4	0.35 ± .0
XI C -10	231	220	265	226 ± 8	0.20 ± .01
XI C -11	967	953	963	960 ± 13	0.95 ± .01
XI C -12	357	354	356	356 ± 2	0.36 ± .0
XI C -13	254	246	240	250 ± 6	0.25 ± .01
XI C -14	371	358	354	364 ± 9	0.37 ± .01

TABLE C.20 SERIES XI – SLOT CHANGES, OTHER MEASUREMENTS

ORIGINAL SERIES - RUN #-S	HUM. (MM WET)	BAR. (MM WET)	O2 %	PPM CO	PPM SO2	CO2 %	ASH %	C IN ASH %	N IN ASH %
XI A - 1	20.3	729	3.1	120	800	----	----	----	----
XI A - 2	19.4	729	2.9	120	775	----	----	----	----
XI A - 3	20.2	729	3.3	100	620	----	----	----	----
XI A - 4	20.5	731	2.8	200	710	----	----	----	----
XI A - 5	21.8	731	2.9	90	635	----	----	----	----
XI A - 6	20.2	731	0.8	3700	840	----	----	----	----
XI A - 7	20.3	731	1.0	3500	740	----	----	----	----
XI A - 8	21.6	731	1.3	120	640	----	----	----	----
XI A - 9	20.3	730	1.0	2200	860	----	----	----	----
XI A -10	20.5	730	0.9	1200	660	----	----	----	----
XI A -11	21.2	730	3.0	75	840	----	----	----	----
XI A -12	21.0	730	3.7	60	690	----	----	----	----
XI A -13	19.1	730	3.0	90	560	----	----	----	----
XI A -14	19.4	730	3.1	100	540	----	----	----	----
XI B - 1	17.0	740	2.8	90	860	----	----	----	----
XI B - 2	18.4	740	3.1	165	810	----	----	----	----
XI B - 3	18.1	740	2.8	115	670	----	----	----	----
XI B - 4	18.4	740	2.6	310	810	----	----	----	----
XI B - 5	17.9	739	3.1	115	760	----	----	----	----
XI B - 6	17.2	738	1.0	2700	900	----	----	----	----
XI B - 7	18.7	737	0.9	2000	820	----	----	----	----
XI B - 8	19.7	737	1.0	1200	800	----	----	----	----
XI B - 9	17.6	737	0.8	8000	770	----	----	----	----
XI B -10	18.2	737	1.0	3200	720	----	----	----	----
XI B -11	17.2	737	2.8	165	900	----	----	----	----
XI B -12	16.1	737	2.9	140	780	----	----	----	----
XI B -13	16.2	737	3.2	150	700	----	----	----	----
XI B -14	16.0	737	3.2	190	650	----	----	----	----
XI C - 1	11.7	739	3.2	150	900	----	----	----	----
XI C - 2	11.8	739	2.9	430	890	----	----	----	----
XI C - 3	12.6	739	2.9	810	700	----	----	----	----
XI C - 4	10.3	739	3.2	1200	850	----	----	----	----
XI C - 5	11.2	738	3.0	300	815	----	----	----	----
XI C - 6	11.4	737	1.0	4000	710	----	----	----	----
XI C - 7	11.8	737	1.1	6500	570	----	----	----	----
XI C - 8	11.0	737	1.1	4000	530	----	----	----	----
XI C - 9	11.4	737	0.6	9500	540	----	----	----	----
XI C -10	11.3	736	0.7	9500	520	----	----	----	----
XI C -11	10.9	735	2.9	125	660	----	----	----	----
XI C -12	11.7	735	3.0	960	490	----	----	----	----
XI C -13	12.8	735	2.8	500	640	----	----	----	----
XI C -14	11.6	735	2.9	260	670	----	----	----	----

TABLE C.21 SERIES XII – BURNER CHANGES, FURNACE DATA (INPUT)

ORIGINAL RUN # AND SERIES OF RUNS	LB. / HR. (DRY WT. / WET WT.)					
	IGNITER (GAS)	FUEL	PRIMARY AIR	SECONDARY AIR	2ND STAGE AIR	FLUE GAS
XII A- 1	3.0	429/449	587/641	4299/4692	0/ 0	0
XII A- 2	3.0	436/457	589/645	3212/3515	1230/1349	0
XII A- 3	3.0	429/450	586/643	2067/2263	2264/2486	0
XII A- 4	3.0	348/365	596/656	2127/2341	1201/1325	0
XII A- 5	3.0	450/472	588/648	2224/2445	2292/2519	0
XII A- 6	3.0	420/446	588/644	3749/4119	0/ 0	0
XII A- 7	3.0	427/448	581/640	2746/3029	1096/1211	0
XII A- 8	3.0	423/443	580/642	1768/1955	2026/2243	0
XII A- 9	3.0	435/456	590/642	2792/3089	1063/1178	0
XII A-10	3.0	443/465	590/642	1943/2147	2061/2282	0
XII A-11	3.0	456/478	588/649	6285/6930	0/ 0	0
XII A-12	3.0	431/452	590/651	4317/4732	0/ 0	0
XII A-13	3.0	319/335	513/562	3059/3353	0/ 0	0
XII A-14	3.0	303/318	518/569	1880/2067	1037/1141	0
XII A-15	3.0	297/311	507/558	897/ 987	2058/2267	0
XII A-16	3.0	307/321	509/561	1958/2155	1090/1203	0
XII A-17	3.0	319/335	507/559	1047/1152	2034/2242	0
XII A-18	2.8	431/452	586/645	4262/4695	0/ 0	0
XII A-19	2.9	434/455	579/637	6006/6603	0/ 0	0
XII A-20	2.9	412/432	586/644	3637/4005	0/ 0	0
XII B- 1	2.9	438/459	592/651	4324/4755	0/ 0	0
XII B- 2	3.0	430/451	583/639	3139/3456	1144/1257	0
XII B- 3	3.0	433/454	600/660	1961/2153	2273/2498	0
XII B- 4	3.0	431/452	600/660	3044/3351	1149/1266	0
XII B- 5	3.0	435/456	610/658	2019/2209	2240/2458	0
XII B- 6	2.9	398/418	608/665	3445/3772	0/ 0	0
XII B- 7	2.9	405/425	592/657	2465/2737	1090/1212	0
XII B- 8	3.0	397/416	593/651	1402/1537	2071/2274	0
XII B- 9	2.9	437/458	586/641	2716/2974	1065/1168	0
XII B-10	2.9	421/441	593/650	1624/1778	2101/2307	0
XII B-11	2.9	434/460	593/652	6066/6657	0/ 0	0
XII B-12	3.0	436/457	585/644	4286/4749	0/ 0	0
XII B-13	3.0	316/331	506/560	3030/3370	0/ 0	0
XII B-14	3.0	317/333	503/561	1963/2189	1062/1186	0
XII B-15	3.0	306/320	506/562	842/ 933	2091/2324	0
XII B-16	3.0	313/328	512/571	1969/2192	1060/1184	0
XII B-17	3.0	325/341	515/571	1173/1299	2012/2232	0
XII B-18	3.1	443/465	594/663	4331/4818	0/ 0	0
XII B-19	3.0	439/460	588/650	5886/6504	0/ 0	0
XII B-20	3.0	421/441	588/650	3657/4044	0/ 0	0
XII C- 1	3.1	440/461	593/659	4310/4771	0/ 0	0
XII C- 2	3.0	432/453	597/661	3020/3349	1154/1276	0
XII C- 3	3.0	417/438	590/654	1877/2075	2239/2483	0
XII C- 4	2.8	427/448	587/650	3024/3348	1140/1264	0
XII C- 5	2.9	434/455	590/653	2011/2221	2241/2483	0
XII C- 6	2.9	402/422	590/652	3424/3786	0/ 0	0
XII C- 7	2.8	389/408	595/656	2188/2412	1117/1233	0
XII C- 8	2.8	383/402	580/639	1102/1212	2245/2474	0
XII C- 9	2.8	410/430	588/648	2393/2641	1147/1267	0
XII C-10	2.9	405/425	590/652	1318/1452	2282/2520	0
XII C-11	2.9	426/447	598/667	5461/5999	0/ 0	0
XII C-12	3.0	444/465	590/655	4294/4771	0/ 0	0
XII C-13	3.0	322/337	508/565	3040/3379	0/ 0	0
XII C-14	3.0	421/441	505/564	3058/3412	1034/1154	0
XII C-15	3.0	321/336	506/563	1054/1176	2008/2236	0
XII C-16	3.0	333/350	526/563	2085/2321	1066/1189	0
XII C-17	3.0	326/342	503/554	1007/1117	2072/2303	0
XII C-18	3.2	436/457	585/646	4298/4751	0/ 0	0
XII C-19	3.1	458/480	585/647	6062/6696	0/ 0	0
XII C-20	3.2	420/440	595/666	3646/4050	0/ 0	0

TABLE C.22 SERIES XII – BURNER CHANGES, FURNACE DATA (FINAL)

ORIGINAL RUN # AND SERIES OF RUNS	TOTAL AIR, %	HEAT, KBTU/FT**3 / HR.	GAS PRE-HEAT DEG. F	FLUE GAS RECYCLED TO INPUT (%)	AIR AT BURNER (%)
XII A- 1	116.3	49.03	620	0.0	116.3
XII A- 2	117.7	48.99	623	0.0	89.9
XII A- 3	117.0	46.45	630	0.0	63.1
XII A- 4	114.6	38.59	598	0.0	79.5
XII A- 5	115.6	48.81	629	0.0	63.9
XII A- 6	104.0	48.91	603	0.0	104.0
XII A- 7	109.6	47.39	607	0.0	79.6
XII A- 8	109.5	45.51	617	0.0	56.6
XII A- 9	104.1	48.26	606	0.0	79.1
XII A-10	105.6	47.71	616	0.0	55.1
XII A-11	153.8	55.65	650	0.0	153.8
XII A-12	116.3	50.22	620	0.0	116.3
XII A-13	113.7	37.02	590	0.0	113.7
XII A-14	115.0	33.69	579	0.0	80.2
XII A-15	118.4	31.56	605	0.0	44.0
XII A-16	117.7	33.87	581	0.0	91.6
XII A-17	114.3	33.80	609	0.0	49.5
XII A-18	115.0	46.53	301	0.0	115.0
XII A-19	155.1	47.79	313	0.0	155.1
XII A-20	104.9	46.31	296	0.0	104.9
XII B- 1	114.6	51.01	620	0.0	114.6
XII B- 2	112.9	49.12	611	0.0	96.3
XII B- 3	113.9	46.76	625	0.0	63.3
XII B- 4	113.3	48.18	598	0.0	86.2
XII B- 5	114.0	47.00	623	0.0	61.4
XII B- 6	103.7	45.58	587	0.0	103.7
XII B- 7	104.4	44.88	601	0.0	76.9
XII B- 8	104.4	42.28	603	0.0	51.2
XII B- 9	102.0	48.34	597	0.0	77.1
XII B-10	104.7	45.03	611	0.0	51.7
XII B-11	155.0	51.44	647	0.0	155.0
XII B-12	114.0	50.69	618	0.0	114.0
XII B-13	113.6	36.63	589	0.0	113.6
XII B-14	113.0	35.13	593	0.0	79.0
XII B-15	114.3	37.22	609	0.0	44.8
XII B-16	115.0	34.66	596	0.0	80.9
XII B-17	115.6	34.58	600	0.0	47.7
XII B-18	113.5	47.96	289	0.0	113.5
XII B-19	150.5	47.96	288	0.0	150.5
XII B-20	102.9	45.11	280	0.0	102.9
XII C- 1	114.0	51.32	628	0.0	114.0
XII C- 2	112.6	48.34	616	0.0	89.6
XII C- 3	115.0	45.11	637	0.0	60.2
XII C- 4	113.7	47.86	628	0.0	88.4
XII C- 5	113.9	46.92	635	0.0	61.1
XII C- 6	101.8	46.06	600	0.0	101.8
XII C- 7	102.1	42.76	594	0.0	72.9
XII C- 8	104.5	40.68	609	0.6	64.7
XII C- 9	102.8	45.11	598	0.0	74.2
XII C-10	105.5	42.99	609	0.0	48.0
XII C-11	145.0	51.24	639	0.0	145.0
XII C-12	112.4	51.56	614	0.0	112.4
XII C-13	112.1	37.10	583	0.0	112.1
XII C-14	111.9	47.00	605	0.0	86.4
XII C-15	113.0	34.03	596	0.0	69.3
XII C-16	111.5	36.86	584	0.0	79.0
XII C-17	111.7	34.50	605	0.0	67.1
XII C-18	114.2	47.24	296	0.0	114.2
XII C-19	148.3	50.30	302	0.0	148.3
XII C-20	103.1	45.14	285	0.0	103.1

TABLE C.23 SERIES XII – BURNER CHANGES, NO_X MEASUREMENTS

ORIGINAL SERIES - RUN #-S	PPM NOX 3% O2, DRY			PPM NOX IN DRY, 3% O2 FLUE GAS	LB. NOX / 10**6 BTU INPUT
	NDIR	TECO	UNIT		
XII A- 1	1182	1200	1201	1191 ± 13	1.22 ± .01
XII A- 2	927	939	1058	933 ± 8	0.97 ± .01
XII A- 3	497	526	579	512 ± 21	0.53 ± .02
XII A- 4	703	736	841	720 ± 23	0.75 ± .02
XII A- 5	552	581	695	567 ± 21	0.58 ± .02
XII A- 6	810	838	1017	824 ± 20	0.77 ± .02
XII A- 7	522	553	690	538 ± 22	0.51 ± .02
XII A- 8	273	286	326	278 ± 8	0.26 ± .01
XII A- 9	426	445	533	436 ± 15	0.41 ± .01
XII A-10	353	374	442	363 ± 15	0.34 ± .01
XII A-11	1336	1310	1629	1327 ± 13	1.78 ± .02
XII A-12	1019	1056	1336	1037 ± 27	1.07 ± .03
XII A-13	872	913	1126	892 ± 29	0.90 ± .03
XII A-14	489	522	584	506 ± 24	0.52 ± .02
XII A-15	332	350	319	341 ± 13	0.36 ± .01
XII A-16	531	550	624	540 ± 14	0.56 ± .01
XII A-17	323	341	319	332 ± 13	0.34 ± .01
XII A-18	977	1027	1104	1002 ± 35	1.02 ± .04
XII A-19	1160	1225	1308	1192 ± 46	1.41 ± .06
XII A-20	738	792	846	765 ± 10	0.78 ± .01
XII B- 1	1196	1244	1393	1220 ± 34	1.24 ± .03
XII B- 2	901	927	1063	914 ± 18	0.92 ± .02
XII B- 3	614	625	600	620 ± 8	0.62 ± .01
XII B- 4	855	875	995	865 ± 15	0.87 ± .01
XII B- 5	555	578	585	566 ± 17	0.57 ± .02
XII B- 6	861	881	968	871 ± 14	0.91 ± .01
XII B- 7	565	587	655	576 ± 16	0.56 ± .01
XII B- 8	298	308	265	303 ± 7	0.28 ± .01
XII B- 9	520	528	598	524 ± 6	0.48 ± .01
XII B-10	299	309	270	304 ± 7	0.28 ± .01
XII B-11	1360	1442	1575	1401 ± 58	1.89 ± .08
XII B-12	1189	1242	1232	1216 ± 38	1.24 ± .04
XII B-13	1011	1033	1075	1022 ± 15	1.04 ± .02
XII B-14	624	639	665	631 ± 10	0.64 ± .01
XII B-15	356	358	371	357 ± 2	0.37 ± .0
XII B-16	605	609	652	607 ± 3	0.63 ± .0
XII B-17	373	393	401	383 ± 14	0.40 ± .01
XII B-18	1040	1052	1176	1046 ± 8	1.08 ± .01
XII B-19	1166	1199	1303	1183 ± 24	1.56 ± .03
XII B-20	756	739	850	748 ± 12	0.69 ± .01
XII C- 1	1099	1117	1129	1108 ± 12	1.13 ± .01
XII C- 2	869	880	904	875 ± 8	0.88 ± .01
XII C- 3	428	424	461	426 ± 3	0.44 ± .0
XII C- 4	737	715	788	726 ± 16	0.74 ± .02
XII C- 5	679	698	956	689 ± 13	0.70 ± .01
XII C- 6	726	726	890	726 ± 0	0.67 ± .0
XII C- 7	406	409	499	408 ± 2	0.37 ± .0
XII C- 8	326	326	372	326 ± 0	0.31 ± .0
XII C- 9	416	425	512	420 ± 6	0.40 ± .01
XII C-10	238	238	282	238 ± 0	0.22 ± .0
XII C-11	1379	1419	1601	1399 ± 28	1.77 ± .04
XII C-12	1153	1190	1219	1172 ± 27	1.18 ± .03
XII C-13	1032	1064	1111	1048 ± 22	1.09 ± .02
XII C-14	347	351	422	349 ± 3	0.35 ± .0
XII C-15	352	349	387	351 ± 2	0.36 ± .0
XII C-16	367	371	493	369 ± 3	0.37 ± .0
XII C-17	289	284	327	287 ± 4	0.29 ± .0
XII C-18	1076	1048	1079	1062 ± 20	1.08 ± .02
XII C-19	1162	1169	1192	1165 ± 5	1.51 ± .01
XII C-20	725	709	752	714 ± 12	0.66 ± .01

TABLE C.24 SERIES XII – BURNER CHANGES, OTHER MEASUREMENTS

ORIGINAL SERIES - RUN #-S	HUM. (MM HG)	BAR. (MM HG)	O2 %	PPM CO	PPM SO2	CO2 %	ASH %	C IN ASH %	N IN ASH %
XII A- 1	10.2	734	3.2	100	1025	----	----	----	----
XII A- 2	11.0	734	3.4	75	960	----	----	----	----
XII A- 3	11.5	734	3.3	68	820	----	----	----	----
XII A- 4	12.4	733	2.9	75	920	----	----	----	----
XII A- 5	12.6	733	3.1	150	850	----	----	----	----
XII A- 6	13.0	733	1.0	3200	1100	----	----	----	----
XII A- 7	12.9	733	1.3	1200	1000	----	----	----	----
XII A- 8	13.7	733	1.3	1600	820	----	----	----	----
XII A- 9	13.7	733	1.0	2600	843	----	----	----	----
XII A-10	15.0	732	1.3	2100	820	----	----	----	----
XII A-11	13.3	732	7.3	140	920	----	----	----	----
XII A-12	11.2	735	3.2	200	820	----	----	----	----
XII A-13	11.0	735	2.8	90	920	----	----	----	----
XII A-14	11.9	735	3.0	80	760	----	----	----	----
XII A-15	12.5	735	3.5	75	690	----	----	----	----
XII A-16	12.6	735	3.4	60	760	----	----	----	----
XII A-17	12.6	735	2.9	150	680	----	----	----	----
XII A-18	12.4	735	3.0	100	960	----	----	----	----
XII A-19	12.2	735	7.4	60	780	----	----	----	----
XII A-20	12.2	735	1.0	2000	960	----	----	----	----
XII B- 1	12.2	731	2.9	65	1050	----	----	----	----
XII B- 2	11.3	731	2.7	130	1000	----	----	----	----
XII B- 3	12.2	730	2.8	300	850	----	----	----	----
XII B- 4	12.4	730	2.8	60	1000	----	----	----	----
XII B- 5	11.4	730	2.8	100	900	----	----	----	----
XII B- 6	10.9	731	0.9	2400	1075	----	----	----	----
XII B- 7	14.5	731	1.1	4300	1000	----	----	----	----
XII B- 8	11.5	731	1.0	1400	850	----	----	----	----
XII B- 9	10.9	731	0.6	3600	950	----	----	----	----
XII B-10	11.4	731	1.1	2150	400	----	----	----	----
XII B-11	12.1	731	7.4	120	975	----	----	----	----
XII B-12	14.2	735	2.8	100	980	----	----	----	----
XII B-13	15.0	735	2.9	200	980	----	----	----	----
XII B-14	15.0	735	2.7	140	850	----	----	----	----
XII B-15	14.8	735	2.9	75	715	----	----	----	----
XII B-16	15.9	735	3.0	55	840	----	----	----	----
XII B-17	14.2	735	3.1	115	730	----	----	----	----
XII B-18	14.6	735	2.8	450	1100	----	----	----	----
XII B-19	13.8	735	7.0	30	910	----	----	----	----
XII B-20	13.4	735	0.8	3900	1050	----	----	----	----
XII C- 1	13.3	735	2.8	60	1025	----	----	----	----
XII C- 2	13.9	735	2.6	330	980	----	----	----	----
XII C- 3	14.3	735	3.0	100	830	----	----	----	----
XII C- 4	13.9	735	2.8	120	960	----	----	----	----
XII C- 5	14.1	735	2.8	300	870	----	----	----	----
XII C- 6	13.3	734	0.6	4400	1090	----	----	----	----
XII C- 7	12.6	735	0.7	9000	1000	----	----	----	----
XII C- 8	12.6	734	1.0	1000	830	----	----	----	----
XII C- 9	12.9	734	0.8	5950	980	----	----	----	----
XII C-10	13.3	734	1.3	2800	810	----	----	----	----
XII C-11	12.2	734	6.5	200	950	----	----	----	----
XII C-12	15.0	735	2.6	200	880	----	----	----	----
XII C-13	14.8	735	2.5	100	950	----	----	----	----
XII C-14	15.9	734	2.6	900	800	----	----	----	----
XII C-15	15.4	734	2.7	155	700	----	----	----	----
XII C-16	15.3	734	2.4	240	880	----	----	----	----
XII C-17	14.8	734	2.5	330	780	----	----	----	----
XII C-18	13.3	734	2.9	500	1020	----	----	----	----
XII C-19	13.4	734	6.8	180	850	----	----	----	----
XII C-20	13.2	734	0.9	1700	1010	----	----	----	----

APPENDIX D

PRELIMINARY DATA PLOTS

The data plots are split up into two groups. First, the original data points are plotted and the appropriate data line(s) drawn to describe the points. Secondly, a blank graph is presented with the "normal", mid air, mid load data line drawn on it. The data plots require the grouping of data into variable ranges which are defined below:

Variable	Range		
	Low	Mid	High
Excess Air, %	< 7.5	7.5 - 25.	> 25.
Load, %	<100.	100. - 125.	>125.
(kBtu/ft^3/hr	< 40.	40. - 50.	> 50.)
Preheat, ^{0}F	<450.	450. - 550.	>550.

These data groupings, although arbitrary, recognize the fact that data were gathered at the extremes and center of the variable ranges studied. The representation of these ranges is:

Variable	Range		
	Low	Mid	High
Excess Air, %	∿ 3	∿ 15	∿ 35
Load, %	∿ 75	∿115	∿140
Preheat ^{0}F	∿350	∿500	∿650

The lines which are drawn through the data points are "eyeball" fits and are simply used to describe the apparent trend of the data. These lines are drawn from visual fitting and no mathematical correlation has been used. The simplest form of line has been drawn through the data points – straight where possible.

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Figure D.23 shows the substoichiometric tests plotted as ppm NO. The line drawn in D.24 was used to calculate the line data for plotting D.55. The data below show these calculations:

% Stoichiometry Burners	NO, ppm; D.23/D.24	% Reduction, NO; D.55
115	1045	≡ 0
112.5	1000	4
100	625	40
95	500	52
85	288	72
70	75	93
60	0	≡ 100

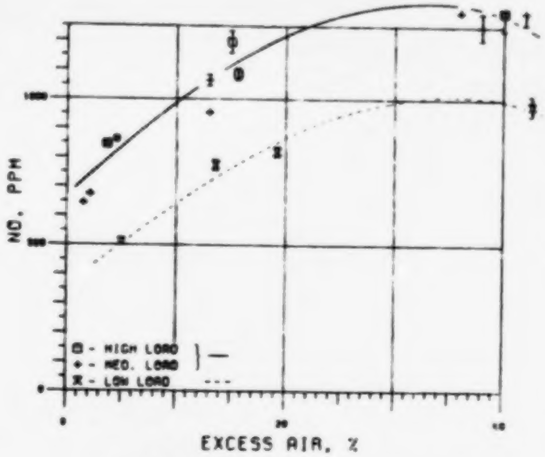


FIGURE D.1 COLORADO – HIGH PREHEAT

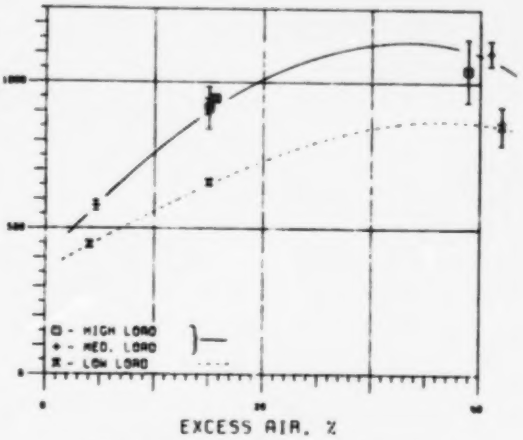


FIGURE D.2 COLORADO – LOW PREHEAT

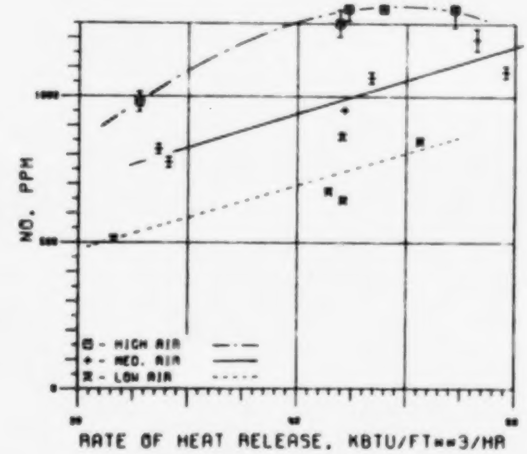


FIGURE D.3 COLORADO – HIGH PREHEAT

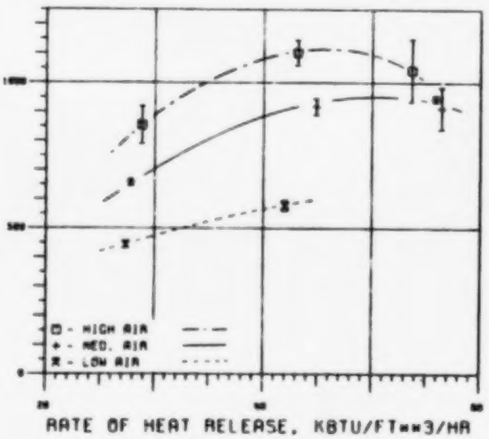


FIGURE D.4 COLORADO – LOW PREHEAT

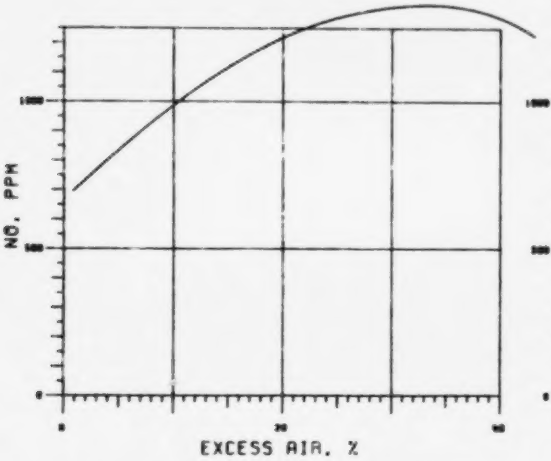


FIGURE D.5 COLORADO – HIGH PREHEAT

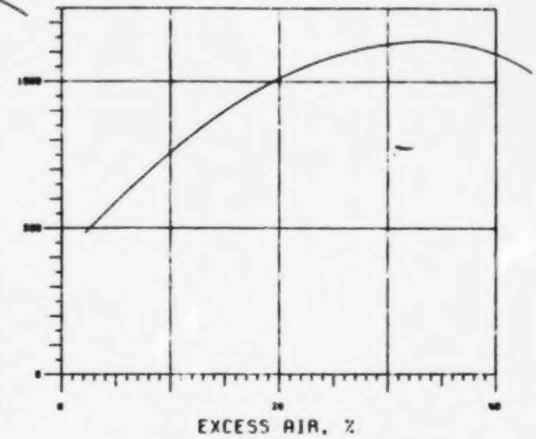


FIGURE D.6 COLORADO – LOW PREHEAT

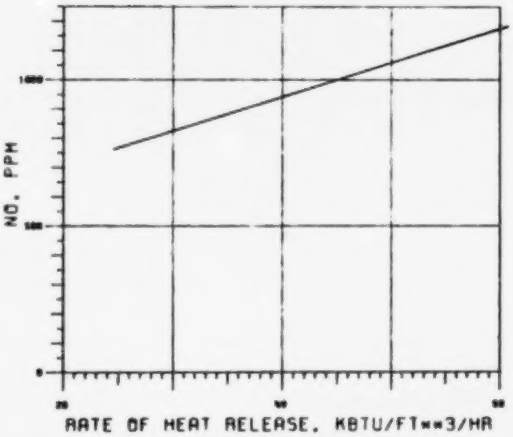


FIGURE D.7 COLORADO – HIGH PREHEAT

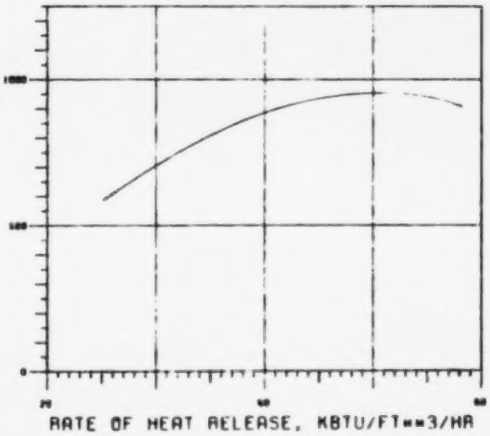


FIGURE D.8 COLORADO – LOW PREHEAT

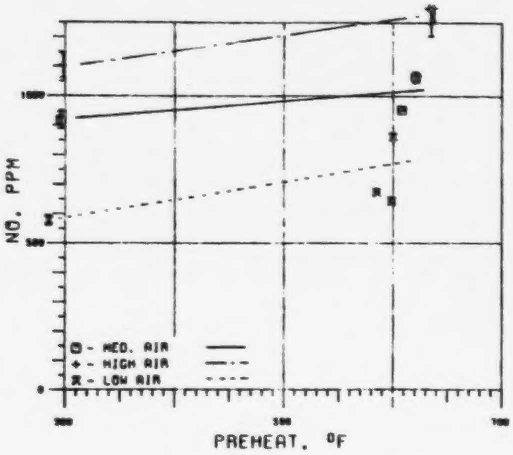


FIGURE D.9 COLORADO – MEDIUM LOAD

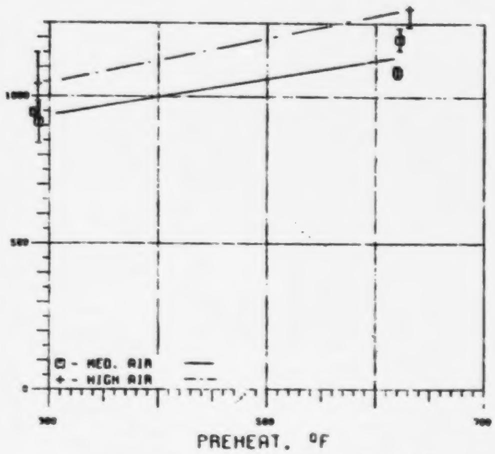


FIGURE D.10 COLORADO – HIGH LOAD

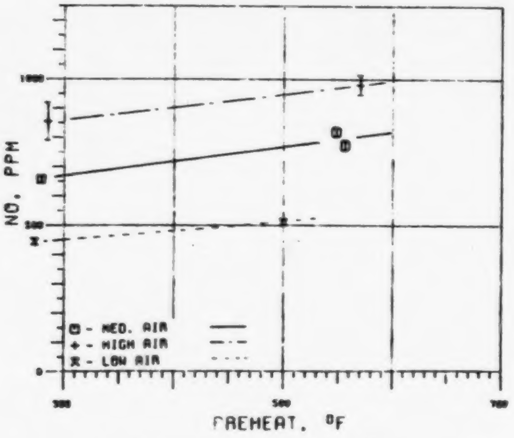


FIGURE D.11 COLORADO – LOW LOAD

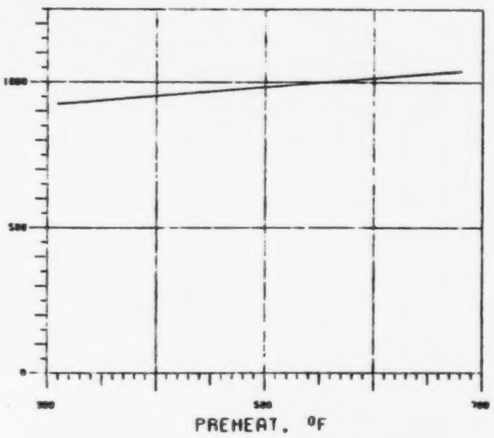


FIGURE D.12 COLORADO – MEDIUM LOAD

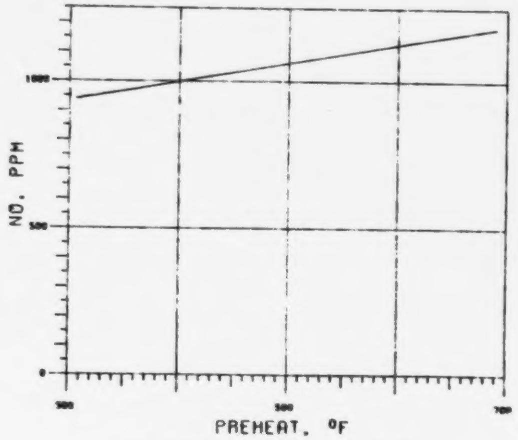


FIGURE D.13 COLORADO – HIGH LOAD

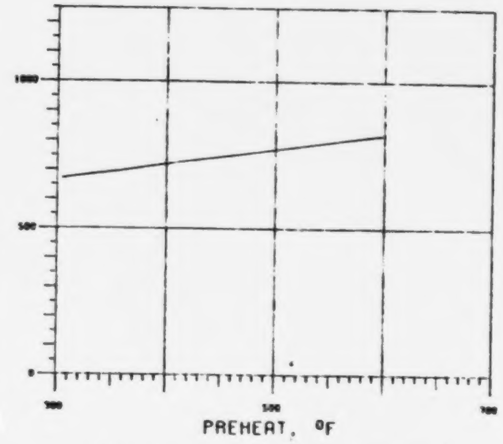


FIGURE D.14 COLORADO – LOW LOAD

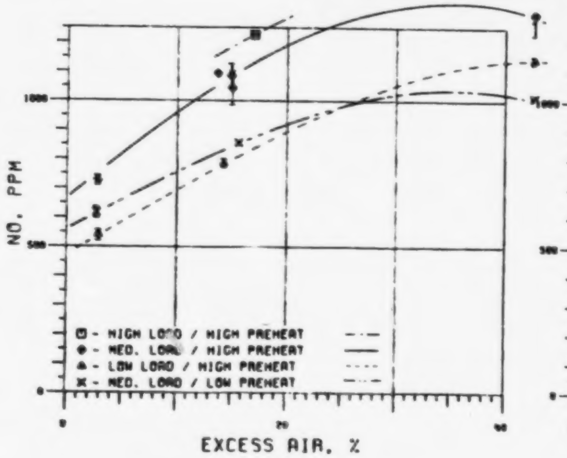


FIGURE D.15 FINE COAL – AIR

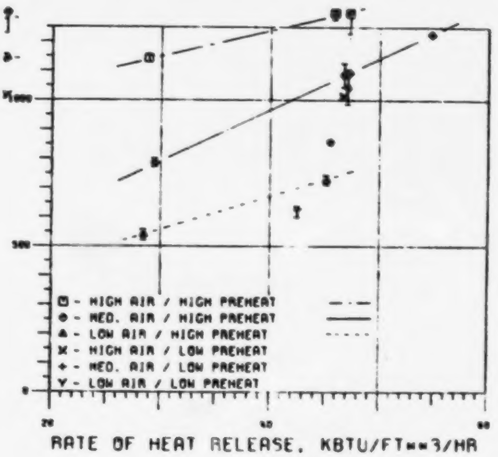


FIGURE D.16 FINE COAL – LOAD

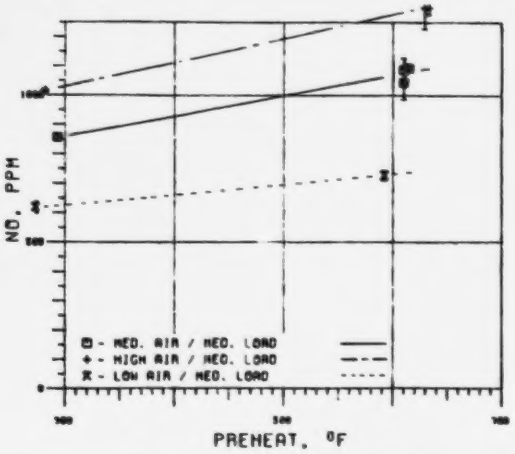


FIGURE D.17 FINE COAL – PREHEAT

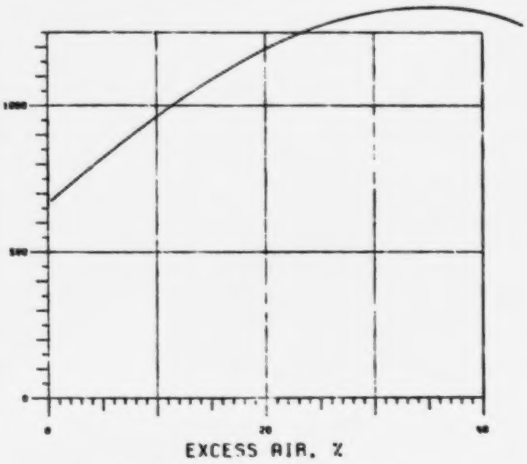


FIGURE D.18 FINE COAL – AIR

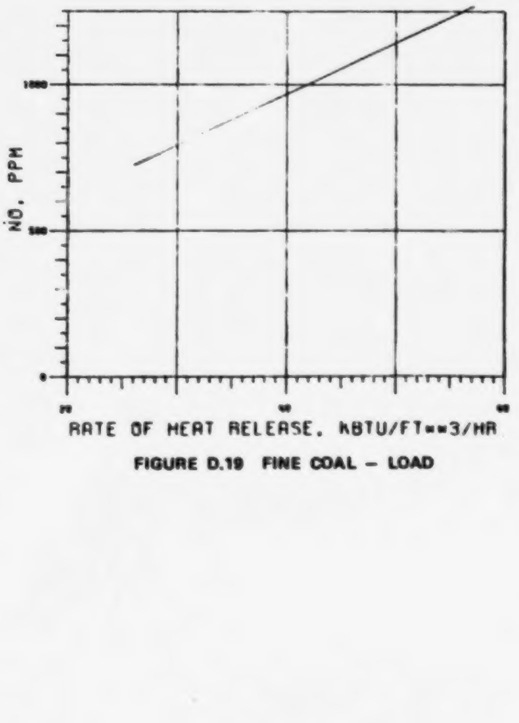


FIGURE D.19 FINE COAL – LOAD

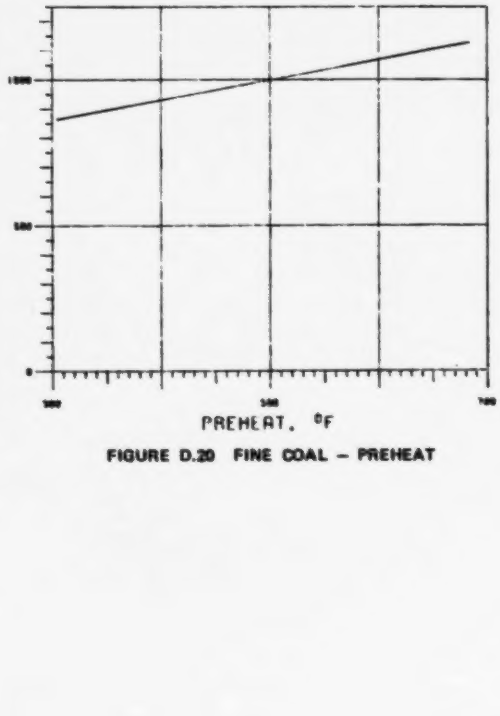


FIGURE D.20 FINE COAL – PREHEAT

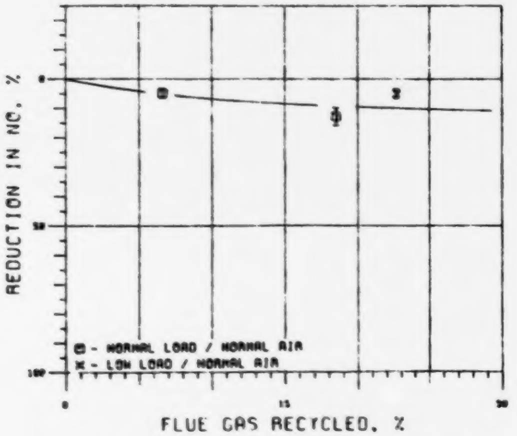


FIGURE D.21 FLUE GAS RECIRCULATION

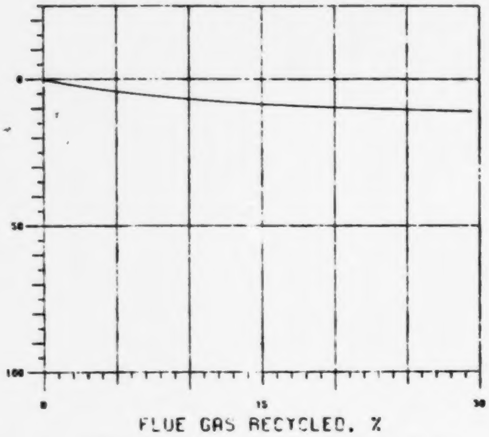


FIGURE D.22 FLUE GAS RECIRCULATION

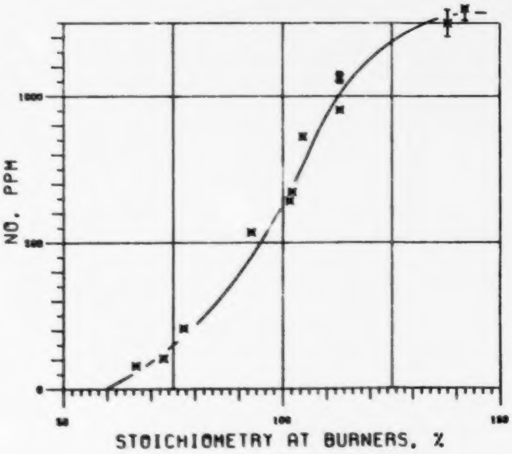


FIGURE D.23 SUBSTOICHIOMETRIC TESTS

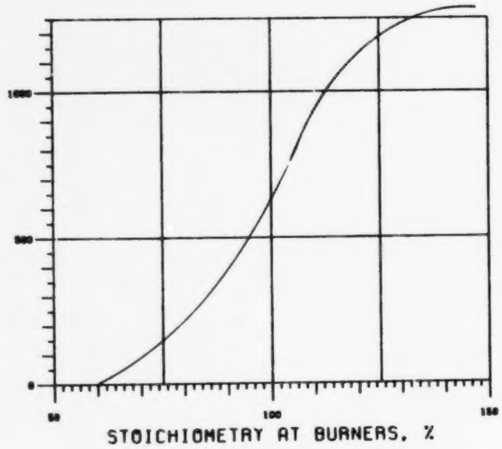


FIGURE D.24 SUBSTOICHIOMETRIC TESTS

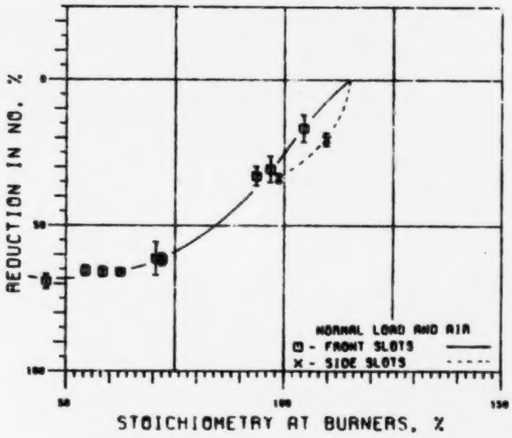


FIGURE D.25 STAGED – PORT VARIABLE

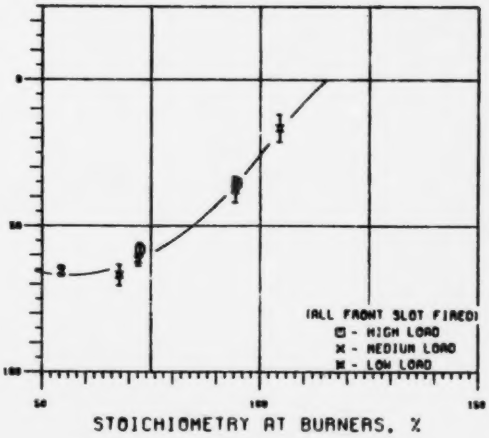


FIGURE D.26 STAGED – 15% EXCESS AIR

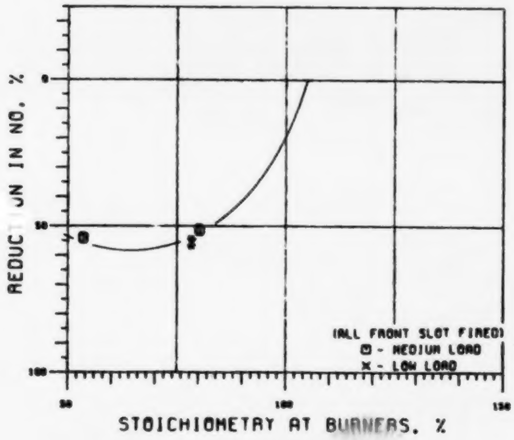


FIGURE D.27 STAGED – 3% EXCESS AIR

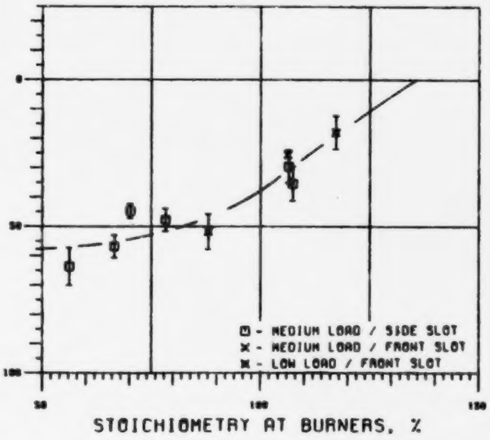


FIGURE D.28 STAGED – 35% EXCESS AIR

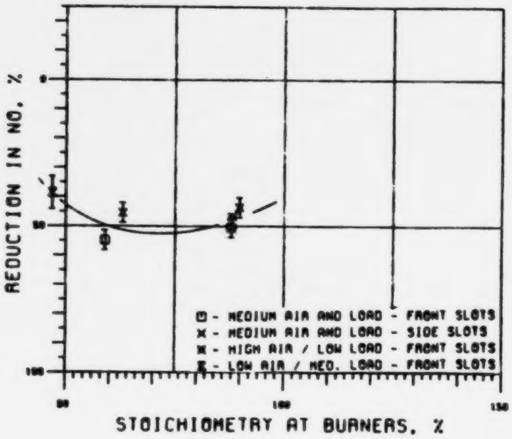


FIGURE D.29 STAGED – LOW PREHEAT

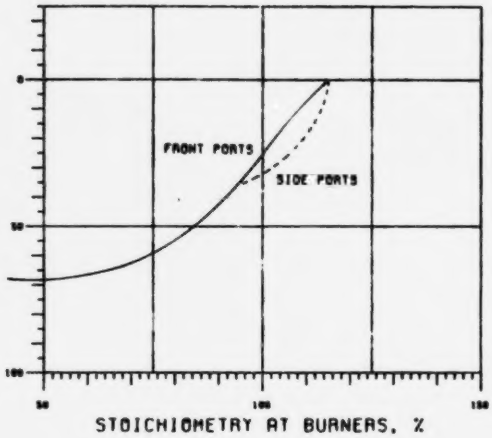


FIGURE D.30 STAGED – PORT VARIABLE

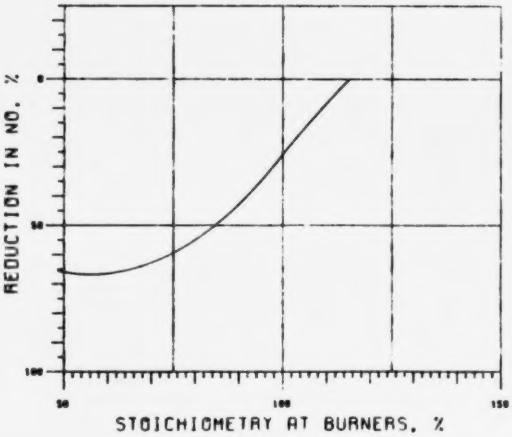


FIGURE D.31 STAGED – 15% EXCESS AIR

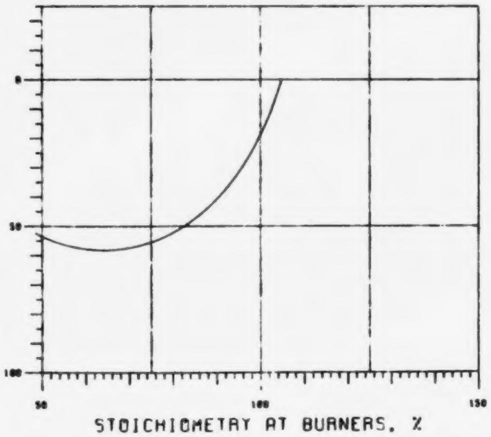


FIGURE D.32 STAGED – 3% EXCESS AIR

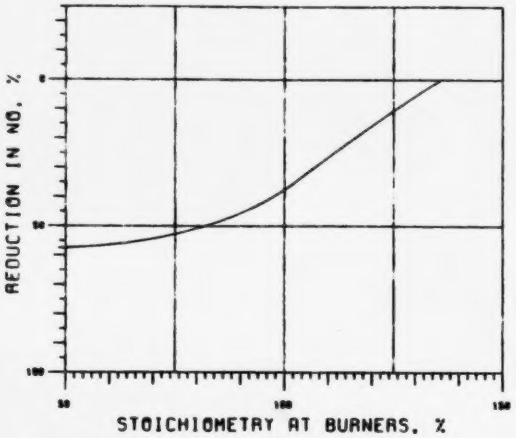


FIGURE D.33 STAGED – 35% EXCESS AIR

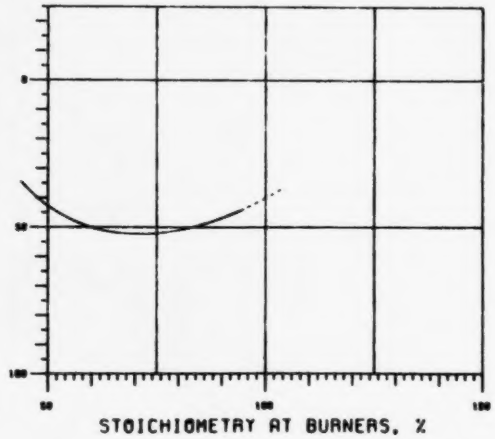


FIGURE D.34 STAGED – LOW PREHEAT

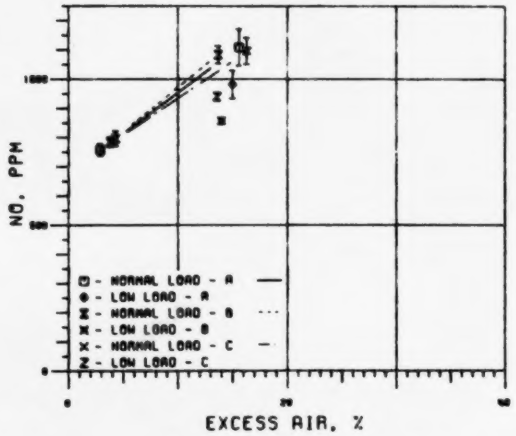


FIGURE D.35 SLOT CHANGES

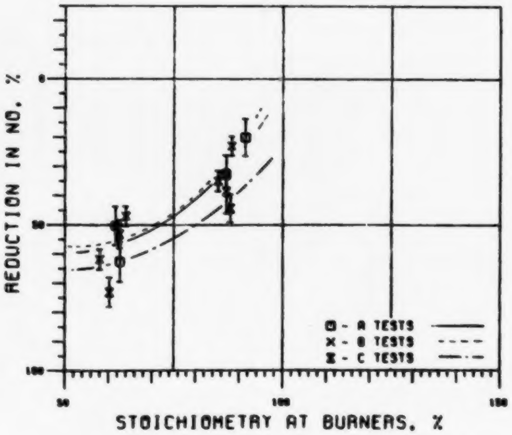


FIGURE D.36 SLOT CHANGES – 15% AIR

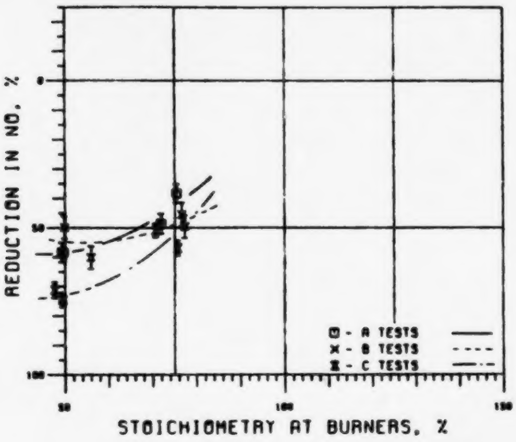


FIGURE D.37 SLOT CHANGES – LOW AIR

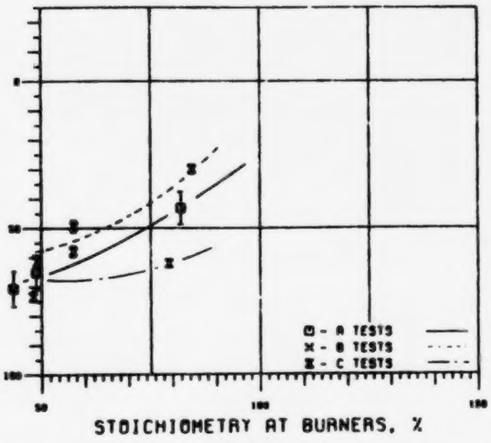


FIGURE D.38 SLOT CHANGES – LOW LOAD

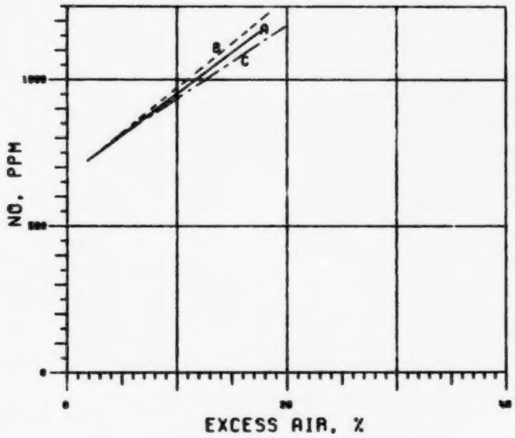


FIGURE D.39 SLOT CHANGES

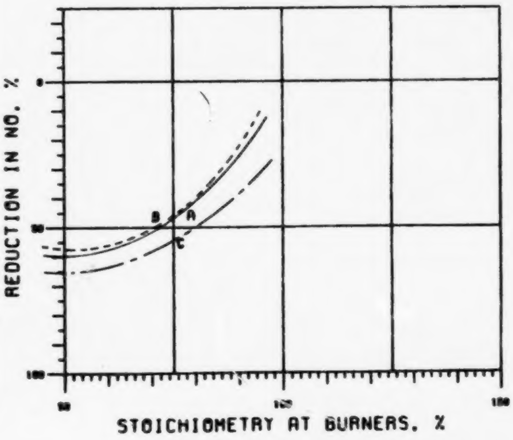


FIGURE D.40 SLOT CHANGES – 15% AIR

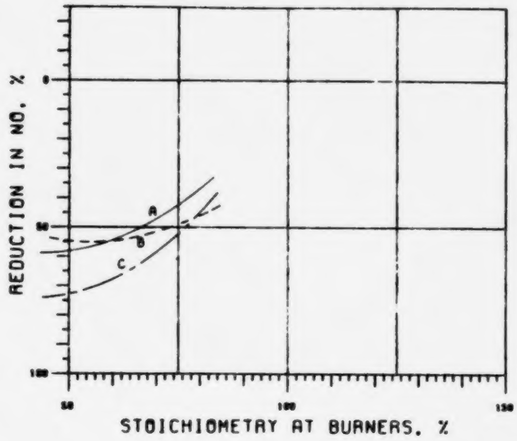


FIGURE D.41 SLOT CHANGES – LOW AIR

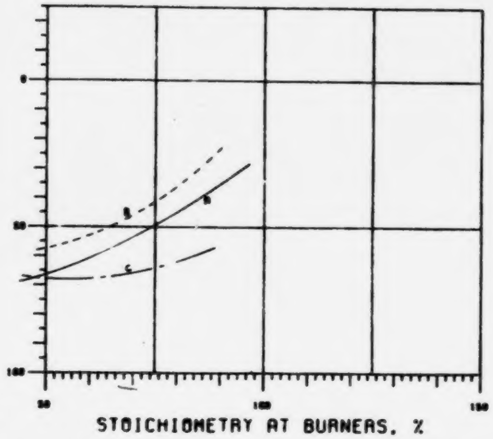
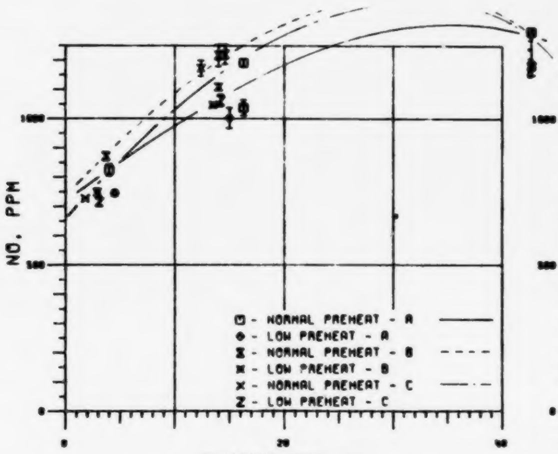
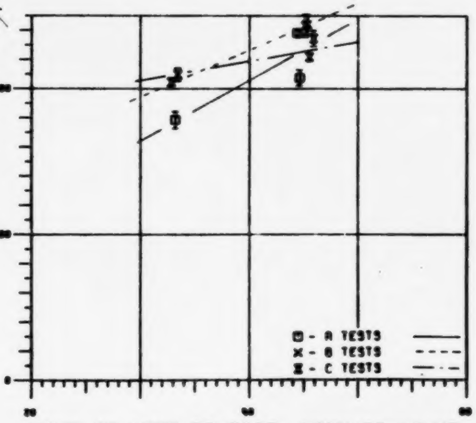


FIGURE D.42 SLOT CHANGES – LOW LOAD



- ⊡ - NORMAL PREHEAT - A
- ◆ - LOW PREHEAT - A
- ⧗ - NORMAL PREHEAT - B
- ✱ - LOW PREHEAT - B
- × - NORMAL PREHEAT - C
- Z - LOW PREHEAT - C

FIGURE D.43 BURNER CHANGES



- ⊡ - A TESTS
- × - B TESTS
- ⧗ - C TESTS

FIGURE D.44 BURNER CHANGES

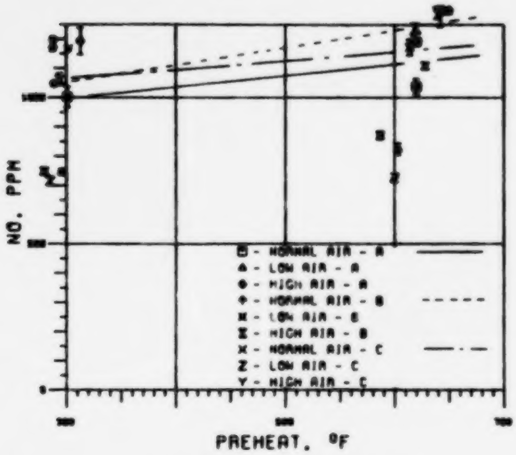


FIGURE D.45 BURNER CHANGES

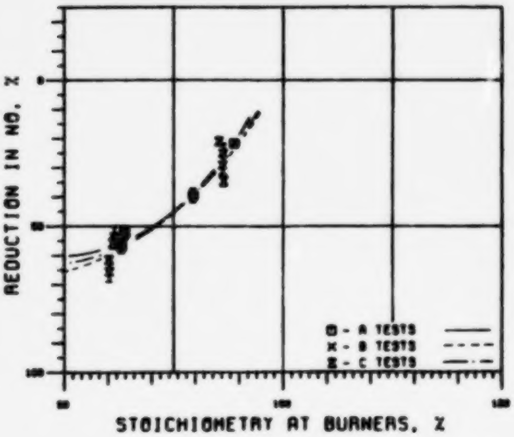


FIGURE D.46 BURNER CHANGES – 10% AIR

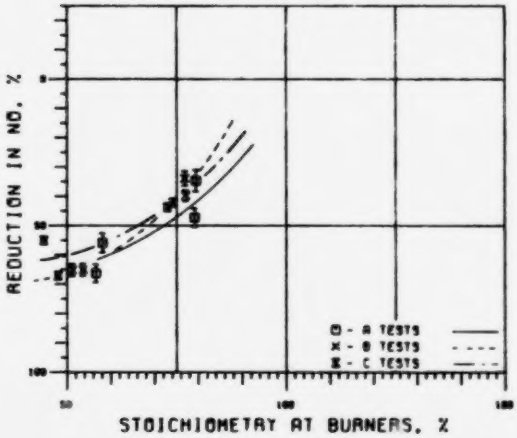


FIGURE D.47 BURNER CHANGES – LOW AIR

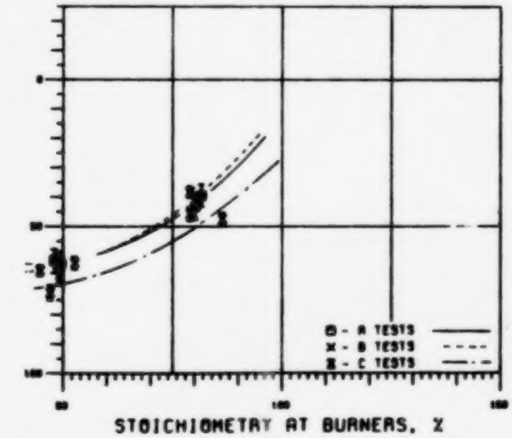


FIGURE D.48 BURNER CHANGES – LOW LOAD

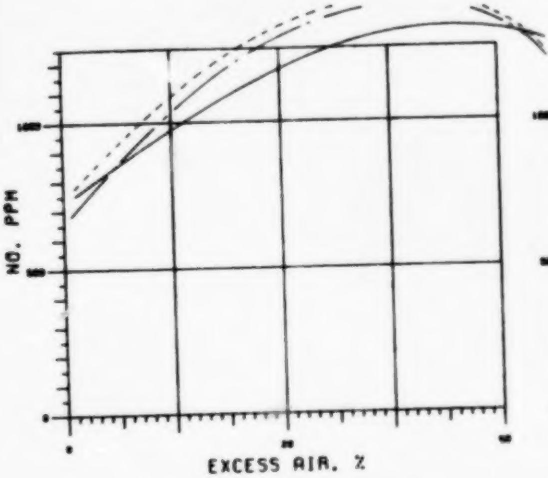


FIGURE D.49 BURNER CHANGES

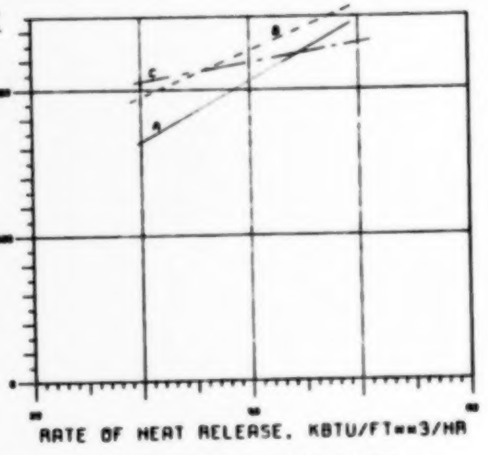


FIGURE D.50 BURNER CHANGES

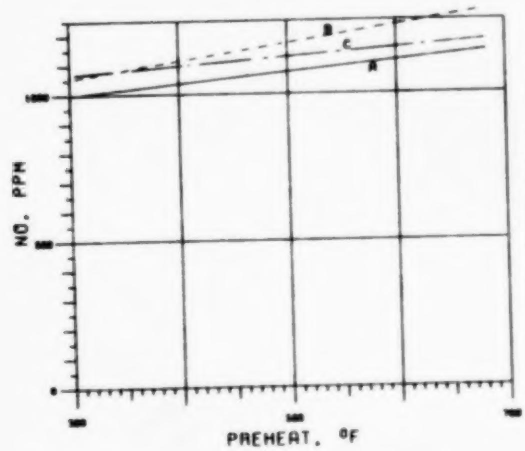


FIGURE D.51 BURNER CHANGES

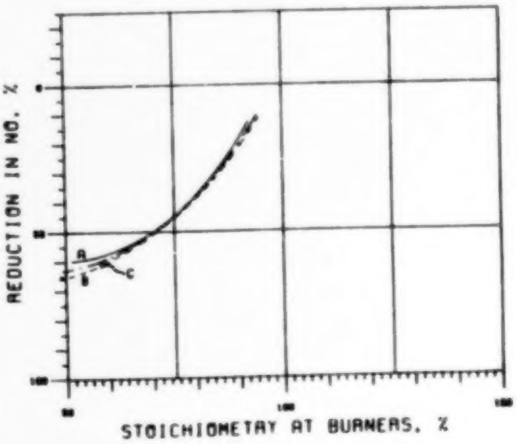


FIGURE D.52 BURNER CHANGES – 15% AIR

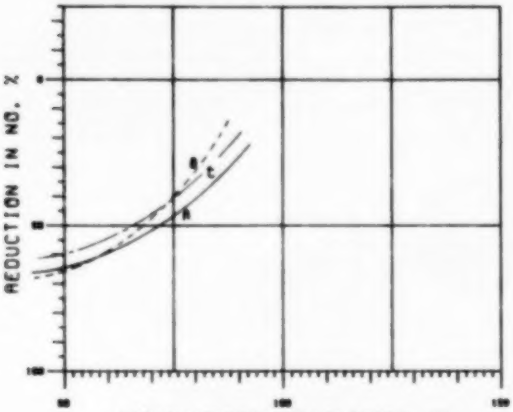


FIGURE D.53 BURNER CHANGES – LOW AIR

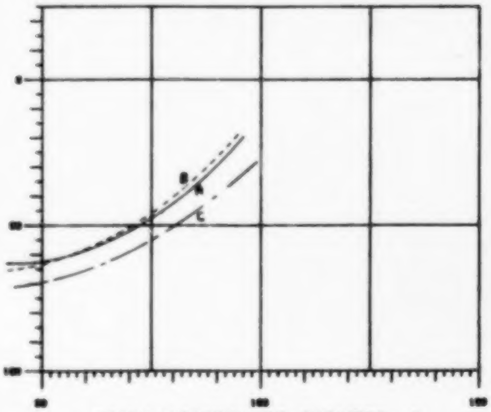


FIGURE D.54 BURNER CHANGES – LOW LOAD

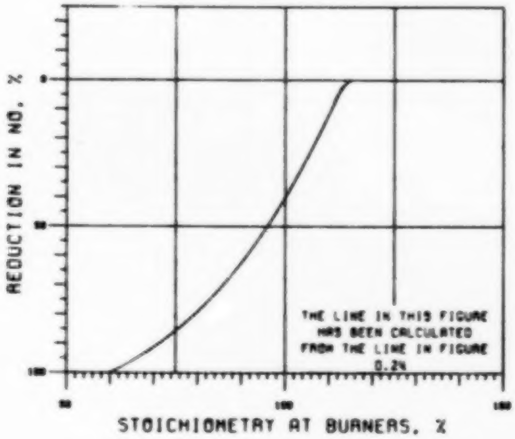


FIGURE D.55 SUBSTOICHIOMETRIC TESTS

APPENDIX E

MATHEMATICAL DERIVATIONS AND CALCULATIONS

Initial calculations were done by computer and yielded the weight of fuel, air, and natural gas from the igniter including any moisture if present (see Appendices A and B). In addition, the percentage of theoretical air was calculated. For large amounts of combustibles (>3%) in the flue gas during substoichiometric tests, a gas chromatographic sample was analyzed for CO and H_2 (and CH_4) to determine equivalent combustibles as CO; or the equivalent CO was hand calculated if the fuel feed had remained steady and primary air rate constant from the previous base test. (The equivalent CO for combustibles assumed all combustible gas was present as CO for ease of excess air calculations — H_2 and CO both required 1/2 O_2 and no other combustibles were found in the flue gas except solid carbon. Since there was little unburned carbon in all coal tests and the amount was relatively constant, it was ignored in these excess air calculations.)

The flue gas recirculation was calculated by taking the ratio of flue gas recycled to the total weight of fuel and air in the combustion:

$$FGR = 100.0 \times \frac{W'_{fg}}{W_a + W_f}$$

The criterion for staging was the stoichiometry at the burner which is given by:

$$PBA = \frac{PTA \times FB}{100.0}$$

where

$$FB = W_2/W_a$$

In addition, corrections were applied to the NO_x instrument readings for CO_2 and H_2O. The following series of constants were used:

Constant Used		Colorado Ohio	Ohio Coal	Gas*
$\frac{\text{Wt of stoich. air}}{\text{Wt of Fuel}}$		9.237	8.588	16.48
Wt of moisture/ 100 lb fuel		4.65	6.13	0.0
MF	MFI	0.6298	0.6298	0.6315
	MFR	0.3380	0.3154	0.6315
MA	MAI	0.5694	0.5694	0.5709
	MAR	0.02664	0.02549	0.1197
MM	MMI	0.1192	0.1192	0.1197
	MMR	0.02664	0.02549	0.1197
MC	MCI	0.06135	0.06135	0.06138
	MCR	0.05816	0.05405	0.06138

The equations are thus given as:

$$TM = MF + \frac{(PTA - 100.0)}{100} \times MA + MMH + MMF$$

where

$$MF = MFI \times W_{NI} + MFR \times W_f$$

$$MA = MAI \times W_{NI} + MAR \times W_f$$

$$NMH = MA \times \frac{P_{H_2O}}{(PB - P_{H_2O})}$$

---

*Gas analysis used for coal igniter firing.

$$\text{MMF} = 0.0465 \text{ lb } H_2O/\text{lb coal (only for Colorado coal)}$$

$$\text{FCO2} = \frac{\text{MC}}{\text{TM}}$$

$$= \frac{\text{MCI} \times W_{NI} + \text{MCR} \times W_f}{\text{TM}}$$

$$\text{FH2O} = \frac{\text{MMI} \times W_{NI} + \text{MMR} \times W_f}{\text{TM}} + \frac{\text{MMH} + \text{MMF}}{\text{TM}}$$

Corrections applied to the NO_x instrumentation are:

Whittaker: Multiply by (1.0 - FH2O - FCO2)
[With bubbler solution, multiply by
(1.0 - FH2O + 0.029268*/(1.0 - FH2O))]
TECo: Multiply by (1.0 - FH2O + 0.012117*/(1.0 - FH2O))
NDIR: Multiply by (1.0 - FH2O + 0.0065342*/(1.0 - FH2O))
after subtraction of 50 ppm correction due to water absorption.†

(The NDIR correction due to water absorption at 34°F saturation was determined experimentally.)

For all: correction to dry, 3% O_2 in flue gas, multiply by:

$$\frac{18.0}{\text{PT} \times (21.0 - \text{POF})} \times \frac{1}{(1.0 - \text{FH2O})}$$

The average of the NDIR and TECo, Aver, was calculated by:

$$\text{Aver} = \frac{\text{NDIR} + \text{TECo}}{2.0}$$

and the standard deviation, STDV, by:

---

*Saturation factor at temperature of measurement.

†Infrared absorption correction for actual water content of sampled flue gas.

$$\text{STDV} = \sqrt{(\text{NDIR} - \text{Aver})^2 + (\text{TECo} - \text{Aver})^2}$$

$$= \sqrt{2.0} \times |\text{TECo} - \text{Aver}|$$

The Btu value from the fuel enthalpy release is given by these equations, one for each fuel:

Colorado Coal: $\text{BTU} = 23855 \times W_{NI} + 12404 \times W_f$

Ohio Coal: $\text{BTU} = 23855 \times W_{NI} + 11533 \times W_f$

Gas: $\text{BTU} = 23920 \times (W_{NI} + W_f)$

The air and recycled flue gas preheat adds enthalpy to the flue gas during combustion also. This addition is given by (no primary preheat):

$$\begin{aligned}\text{BTUG} = {} & \text{BTU} + W_a \times \text{BTU}_a + (\text{MM} \times W_f \times 18.016 + \\ & (\text{MMH} + \text{MMF}) \times 18.016) \times \text{BTU}_m + W'_{fg} \times \text{BTU}_f\end{aligned}$$

where

$$\text{BTU}_a = (\text{TAG} - \text{TA}) \times (0.240 + 10^{-5} \times \text{TAG})$$

$$\text{BTU}_m = (\text{TAG} - \text{TA}) \times (0.444 + 2 \times 10^{-5} \times \text{TAG})$$

and

$$\text{BTU}_f = (\text{TFG} - \text{TA}) \times (0.252 + 10^{-5} \times \text{TFG})$$

For correction of ppm NO_x at 3% O_2, dry flue gas conditions to lb NO_x (as NO) per million Btu (fuel Btu only) input, the NO value is multiplied by:

$\dfrac{W_{fg}}{\text{BTU}}$ (No conversion constant is necessary since the Btu and ppm must both be divided by 10^6.)

In conversion of load percentages to thousands of Btu per ft^3 per hour, the factors to be remembered are:

1) furnace volume - ~127 ft^3 (8 ft long, 4.5 ft diameter)

2) 100% load ≡ 5,000,000 Btu per hr

and therefore if million Btu load is divided by 0.1272, the result is in $kBtu/ft^3/hr$.

For calculation of the fractional reduction, L_3, of the measured values L_1 (base point) and L_2 (reduced value with reduction modification in firing test):

$$L_3 = \frac{L_1 - L_2}{L_1}$$

and since the values were

$$L_1 \pm L_1' \quad \text{and} \quad L_2 \pm L_2'$$

then

$$L_3' = \sqrt{\frac{\left(L_1'^2 + L_2'^2\right)^2}{L_1^2} + \left(\frac{\left(L_1 - L_2\right) \quad x \; L_1'}{L_1^2}\right)^2}$$

The calculations as used in data tables and graphs do not include conversion to the SI/metric system. It is intended that these conversions can be made by consultation of Appendix H. In this way, all data presented in the Phase II final report is consistent and directly comparable to the data in the previous Phase I final report.

APPENDIX F

FUEL NITROGEN CONTENT OF THE OHIO AND COLORADO COALS

A direct comparison of the fuel bound nitrogen content* of the Ohio and Colorado coals was necessary to determine the effect on the NO_x emission levels. There were six samples of Ohio coal and five samples of Colorado coal analyzed for total nitrogen content simultaneously for statistical purposes. All of the samples had been collected at different times and therefore were representative of the nitrogen content and its variability over a long period of time. In the case of the Ohio coal, the samples covered the entire period of Phase I. For the Colorado coal, the samples covered the first half of Phase II.

A blank was run at the same time the eleven samples were analyzed. The results of the analyses are shown in Table F.1. Figure F.1 shows a one dimensional illustration of these samples with nitrogen percentage in the horizontal: the banded regions are the average with $\pm 1\ \sigma$ shown as the total band width.

As can be seen from these data, the two separate sets of fuel bound nitrogen as determined for the coals are statistically identical. The two coals do not differ in fuel bound nitrogen content.

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*The fuel bound nitrogen was determined by the Kjeldahl method.

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TABLE F.1 FUEL BOUND NITROGEN CONTENT

	Nitrogen Content, %	
Sample No.	Ohio Coal	Colorado Coal
1	1.18	1.18
2	1.15	1.20
3	1.13	1.07
4	1.11	1.12
5	0.98	1.25
6	1.07	--
Average of above	1.105	1.164
Standard deviation on average, σ	±0.073	±0.070
Statistical band	1.032 - 1.178	1.094 - 1.234
Statistically determined fuel bound nitrogen	1.1 ± 0.1	1.2 ± 0.1

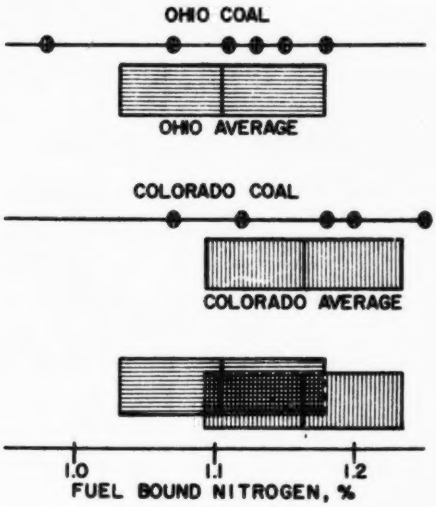

FIGURE F.1 FUEL BOUND NITROGEN CONTENT

APPENDIX G

COMPARATIVE DATA FOR THE OHIO COAL AND NATURAL GAS

The figures included, G.1 to G.7, show the most important trends of the NO_x emission levels from the Ohio coal and natural gas tests. All of these test results have been taken from the Phase I report.

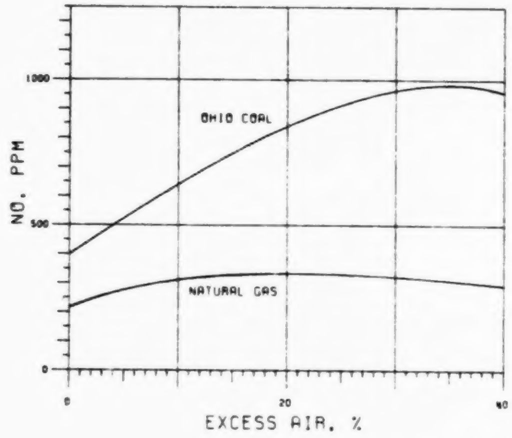

FIGURE G.1 EXCESS AIR

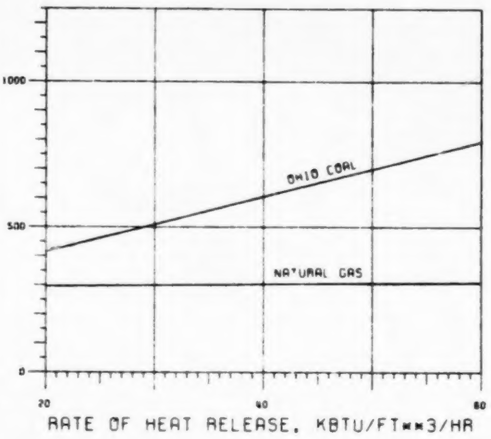

FIGURE G.2 LOAD

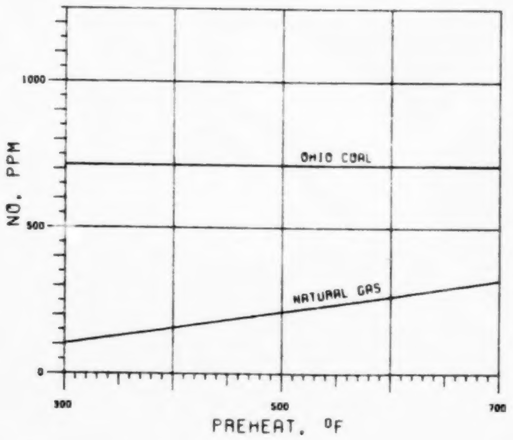

FIGURE G.3 PREHEAT

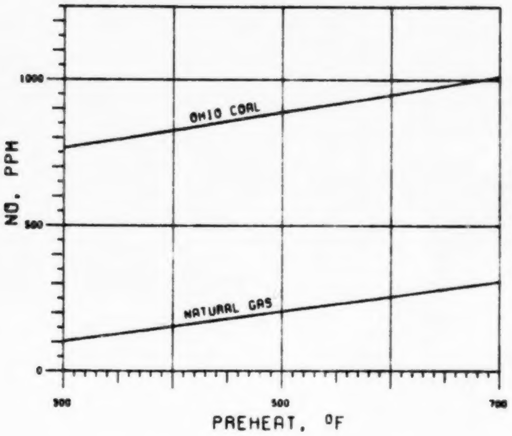

FIGURE G.4 PREHEAT, HIGH EXCESS AIR

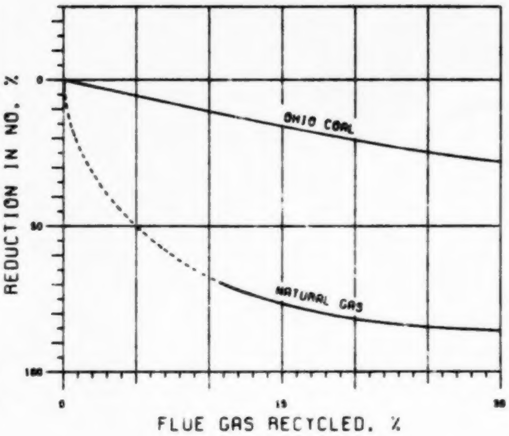

FIGURE G.5 SECONDARY FLUE GAS REC.

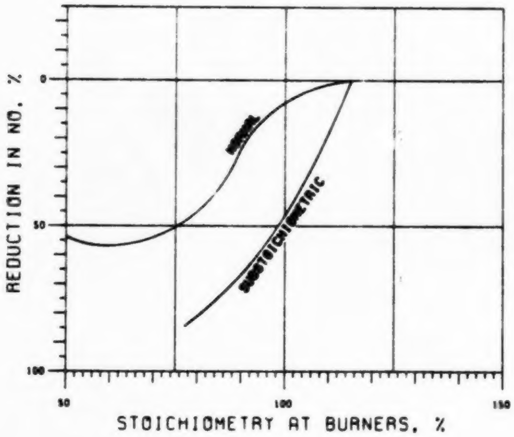

FIGURE G.6 COAL, STAGED COMBUSTION

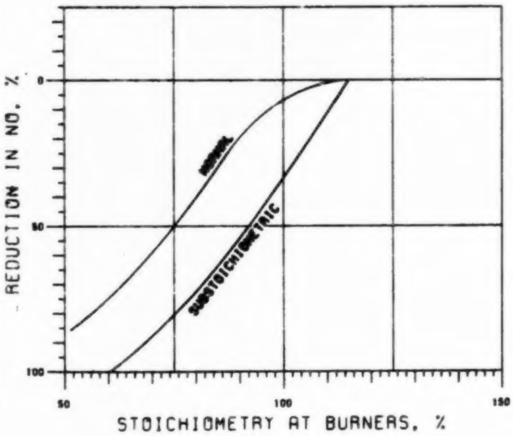

FIGURE G.7 GAS, STAGED COMBUSTION

APPENDIX H

TABLE OF CONVERSION FACTORS FOR SI UNITS

The most important factors for conversion from the English system of measurements to the SI system are:

(One of each of the following)

English units	to	SI Units (to 4 significant figures)*
atmosphere (normal)	=	1.013 E + 05 pascals (Pa)†
atmosphere (technical is 1 kgf/cm^2)	=	9.807 E + 04 " "
British thermal unit (Inter. Table)	=	1.055 E + 03 joules (J)
Btu (mean)	=	1.056 E + 03 " (J)
Btu (thermochemical)	=	1.054 E + 03 " (J)
Btu/pound mass	=	2.326 E + 03 joules/kilogram (J/kg)
Btu/lbm·^{o}F	=	4.187 E + 03 joules/kg·Kelvin (J/kgK)
Btu/hour	=	2.931 E - 01 watts (W)
degrees Farenheit	=	(t^{o}F + 459.7)/1.8 Kelvins (K)
foot	=	3.048 E - 01 meters (m)
pound-mass	=	4.536 E - 01 kilograms (kg)
pound-force	=	4.448 E + 00 newtons (N)
poundal	=	1.383 E - 01 newtons (N)

*The number 1.013 E + 05 is equivalent to 1.013 x 10^5

†The symbol for the unit follows in parentheses

The following table is included for sample conversions from English units to metric units:

(One of each of the following)

English units	to	Metric units
atmosphere	=	76 cm Hg 1.01 3E + 06 degrees/sq.cm 1.03 3E + 00 kg/sq.cm
British thermal unit (International)		2.520 E + 02 (g)cal 2.520 E - 01 (kg)Cal
Btu (mean)		
Btu (thermochemical)		
Btu/pound mass		5.556 E-01 (g)cal/gram 5.556 E-01 (kg)Cal/kg
Btu/lbm$^{\circ}$F		1.0 E + 00 (g)cal/gram $^{\circ}$C 1.0 E + 00 (kg)Cal/kg$^{\circ}$C
Btu/hour		2.520 E + 02 (g)cal/hr 2.520 E - 01 (kg)Cal/hr
degrees Farenheit	=	(tF - 32)/1.8 degrees Centrigrade
foot	=	3.048 E - 01 meters (m)
pound-mass	=	4.536 E - 01 kilograms (kg)
pound-force	=	4.448 E + 00 newtons (N)
Poundal	=	1.383 E - 01 newtons (N)

APPENDIX I

COMBUSTIBLE AND NO_X

Table I.1 is all of the data from the coal and natural gas testing that has been run for this EPA contract. The data include:

Test Numbers — the series number and test number within the series (all Phase I and Phase II tests are included)

Comments — deviations to the usual base testing such as staging, flue gas recirculation, etc.

CO, ppm — the as read, "raw" data

NO, ppm — corrected to 3% O_2, dry

O_2, ppm — the as read, "raw" data

— subheadings separate the Ohio coal, natural gas, and Colorado coal.

The figures I.1 to I.12 show the CO emission levels plotted against either the NO emission levels or the O_2 levels in the flue gas for single tests. (For any single test, a point is plotted.) It should be noted that odd numbered graphs (I.1, I.3, I.5, etc.) are log (CO) and the even numbered graphs are just CO.

Observations

For the Ohio coal, the log (CO) plots show a better picture of the pattern. A somewhat linear dependency of the log (CO) on O_2 is indicated.

The natural gas curves show the same type of variation with NO and O_2, although the absolute values of CO are lower than for the Ohio coal. The dependency of the log (CO) on O_2 is less linear and shows a leveling out at >3% O_2.

The Colorado coal again shows the same trends as the Ohio coal and natural gas. The absolute values of CO emission are similar to the Ohio coal. (A single curve could fit all data I.3 and I.11) The log (CO) versus O_2 is almost linear.

TABLE I.1 COMPARISON OF ALL PHASE I AND PHASE II WORK

TEST NOS.	COMMENTS	CO, PPM	NO, PPM	O2, %
	OHIO COAL			
I - 1		205	725	3.2
I - 2		80	913	6.2
I - 3		8300	431	0.8
I - 4		180	714	2.4
I - 5		90	948	5.5
I - 6		9300	431	0.9
I - 7		260	740	2.7
I - 8		115	998	5.7
I - 9		15000	544	1.0
I - 10		115	534	2.4
I - 11		9000	292	0.8
I - 12		85	395	5.6
I - 13		240	544	2.4
I - 14		560	808	2.9
I - 15		500	683	2.7
I - 16		4300	420	0.7
I - 17		70	834	6.0
I - 18		65	821	5.5
I - 19		240	660	2.5
I - 20		3200	321	1.1
I - 21		60	681	5.9
I - 22		90	985	6.0
I - 23		165	791	2.5
I - 24		20000	282	0.8
I - 25		400	766	2.2
I - 26		6000	539	0.9
I - 27		140	956	5.5
I - 28		100	676	2.7
I - 29		800	624	2.3
I - 30		400	601	2.4
I - 31		18000	312	1.6
I - 32		375	731	5.1
I - 33		50	950	6.1
I - 34		4500	466	0.9
I - 35		260	789	3.2
I - 36		400	749	6.2
I - 37		50	822	6.0
I - 38		750	834	5.1
I - 39		3000	558	1.3
I - 40		90	739	3.7
I - 41		3200	444	1.2
I - 42		360	766	5.4
I - 43		7000	509	0.7
IIA - 1		90	776	2.9
IIA - 2	PRIMARY FGR	80	694	2.6
IIA - 3	PRIMARY FGR	90	659	2.7
IIA - 4		100	898	5.3
IIA - 5	PRIMARY FGR	90	898	5.2
IIA - 6		6000	449	0.8
IIA - 7	PRIMARY FGR	3200	472	0.7
IIA - 8		90	829	2.8
IIA - 9	PRIMARY FGR	90	740	2.8
IIA - 10		140	980	5.7
IIA - 11	PRIMARY FGR	140	969	6.0
IIA - 12		100	762	2.8
IIA - 13	PRIMARY FGR	85	796	2.8
IIA - 14		1500	571	0.9
IIA - 15	PRIMARY FGR	2600	557	0.8
IIA - 16		660	670	2.8
IIA - 17	PRIMARY FGR	240	494	2.8
IIA - 18	PRIMARY FGR	90	699	5.5
IIA - 19		90	658	5.1
IIA - 20		4300	246	1.0
IIA - 21	PRIMARY FGR	4900	251	0.9
IIA - 22		90	654	2.8
IIA - 23	PRIMARY FGR	125	635	2.4
IIA - 24	PRIMARY FGR	115	868	5.6
IIA - 25		105	913	5.5
IIA - 26		4000	444	0.5
IIA - 27	PRIMARY FGR	4000	387	0.6
IIA - 28	PRIMARY FGR	240	630	2.6
IIA - 29		190	667	2.5
IIA - 30		350	452	2.5
IIA - 31	PRIMARY FGR	200	901	3.3
IIA - 32		165	613	2.6
IIA - 33	PRIMARY FGR	260	622	2.3
IIA - 34		90	706	5.0
IIA - 35	PRIMARY FGR	90	734	5.0
IIA - 36		115	910	5.4
IIA - 37	PRIMARY FGR	115	791	5.3
IIB - 1		115	824	3.3
IIB - 2	SECONDARY FGR	115	709	3.0
IIB - 3		165	499	3.6
IIB - 4	SECONDARY FGR	115	416	3.6
IIB - 5	SECONDARY FGR	100	532	6.2
IIB - 6		100	722	6.0
IIB - 7		2600	333	1.8
IIB - 8	SECONDARY FGR	1500	258	1.5
IIB - 9		83	832	2.9
IIB - 10		60	1080	6.3
IIB - 11		4000	289	0.8
IIB - 12		90	1014	6.2
IIB - 13		80	833	5.3
IIB - 14	SECONDARY FGR	70	545	3.6
IIB - 15		80	1044	5.9
IIB - 16	SECONDARY FGR	90	797	6.0
IIB - 17		2000	552	1.0
IIB - 18	SECONDARY FGR	1400	372	1.0
IIB - 19		100	576	3.3
IIB - 20	SECONDARY FGR	90	392	3.3
IIB - 21		80	810	5.3
IIB - 22	SECONDARY FGR	40	596	6.2
IIB - 23		3900	370	1.1
IIB - 24	SECONDARY FGR	490	242	1.1
IIB - 25		70	1013	5.5
IIB - 26	SECONDARY FGR	80	914	5.3
IIB - 27		4000	539	0.8
IIIA - 1		90	892	3.0
IIIA - 2		60	1051	5.5
IIIA - 3		1300	580	0.4
IIIA - 4		80	859	2.5
IIIA - 5		160	1123	6.1
IIIA - 6		190	624	3.0
IIIA - 7		115	865	5.6
IIIA - 8		90	830	2.8
IIIA - 9		400	797	3.1
IIIA - 10		0	869	5.1
IIIA - 11		225	765	5.1
IIIA - 12		1000	534	0.8
IIIA - 13		1150	641	0.9
IIIA - 14		1055	885	3.0
IIIA - 15		1175	981	0.8
IIIA - 16		200	942	5.7
IIIA - 17		760	739	2.8
IIIA - 18		165	1001	5.6
IIIA - 19		210	605	3.4
IIIA - 20		240	770	5.6
IIIA - 21		7000	294	0.9
IIIB - 1	STAGED	115	677	3.2
IIIB - 2	STAGED	140	408	3.2
IIIB - 3	STAGED	130	505	3.8
IIIB - 4	STAGED	170	711	3.4
IIIB - 5	STAGED	175	345	3.2
IIIB - 6	STAGED	475	295	3.0
IIIB - 7	STAGED	650	467	3.2
IIIB - 8	STAGED	1050	350	3.2
IIIB - 9	STAGED	1125	432	3.2
IIIB - 10	STAGED	300	753	3.2
IIIB - 11	STAGED	285	395	3.3
IIIB - 12	STAGED	300	350	3.6
IIIB - 13	STAGED	285	376	2.9
IIIB - 14	STAGED	210	384	3.1
IIIB - 15	STAGED	4000	399	0.8
IIIB - 16	STAGED	3250	283	0.9
IIIB - 17	STAGED	2600	371	0.9
IIIB - 18	STAGED	1175	693	3.2
IIIB - 19	STAGED	1100	409	3.1
IIIB - 20	STAGED	1600	656	3.4
IIIB - 21	STAGED	2150	524	0.8
IIIB - 22	STAGED	1000	334	0.9
IIIB - 23	STAGED	4000	440	1.5
IIIB - 24	STAGED	200	689	5.7
IIIB - 25	STAGED	250	685	5.8
IIIB - 26	STAGED	260	674	3.8
IIIB - 27	STAGED	200	807	5.4
IIIB - 28	STAGED	210	844	5.7
IIIB - 29	STAGED	2800	281	2.9
IIIB - 30	STAGED	1500	362	2.6
IIIB - 31	STAGED	285	410	5.8
IIIB - 32	STAGED	285	524	6.0
IIIC - 1	FGR, STAGED	240	320	3.1
IIIC - 2	FGR, STAGED	310	465	3.3
IIIC - 3	FGR, STAGED	0	366	5.0
IIIC - 4	FGR, STAGED	460	411	3.2
IIIC - 5	FGR, STAGED	1050	325	0.6
IIIC - 6	FGR, STAGED	900	655	3.2
IIID - 1	SUBSTOICHIOMETRIC	12000	377	0.0
IIID - 2	SUBSTOICHIOMETRIC	47000	203	0.0
VA - 13	STAGED	550	698	3.1
VA - 14	STAGED	75	649	3.1
VA - 15	FGR	2500	717	3.2
VA - 16		450	791	3.2
VA - 17		200	871	5.6
VA - 18		1050	790	3.1
VA - 19		285	834	5.3
VA - 20		2700	550	0.9
VI - 1		285	707	3.0
VI - 2	STAGED	810	555	3.1
VI - 3	STAGED	660	471	3.1
VI - 4	FGR	500	603	3.3
VI - 5		620	829	5.0
VI - 6		2225	545	1.4
VI - 7		750	766	3.4
VI - 8		720	899	4.2

TABLE I.1 (CON'T) COMPARISON OF ALL PHASE I AND PHASE II WORK

TEST NOS.	COMMENTS	CO, PPM	NO, PPM	O_2, %
	NATURAL GAS			
IVA - 1		190	322	2.9
IVA - 2		183	320	4.0
IVA - 3		113	267	0.6
IVA - 4		70	300	3.0
IVA - 5		93	318	4.9
IVA - 6		810	249	0.7
IVA - 7		40	303	2.0
IVA - 8		40	311	4.9
IVA - 9		490	249	0.0
IVA - 10		40	168	2.0
IVA - 11		40	135	4.0
IVA - 12		1070	123	0.7
IVA - 13		35	144	2.0
IVA - 14		40	127	3.6
IVA - 15		1070	124	0.7
IVA - 16		23	156	2.0
IVA - 17		980	109	0.9
IVA - 18		15	139	4.0
IVA - 19	FGR	7	46	3.1
IVA - 20	FGR	22	76	3.1
IVA - 21	FGR	22	67	4.0
IVA - 22	FGR	200	60	0.0
IVA - 23	FGR	133	33	3.7
IVA - 24	FGR	22	54	2.0
IVA - 25	FGR	400	24	0.0
IVA - 26		0	346	3.1
IVA - 27	STAGED	0	256	3.0
IVA - 28	FGR, STAGED	3	23	2.7
IVA - 29	FGR, STAGED	7	178	2.9
IVA - 30	STAGED	40	90	3.2
IVA - 31	FGR, STAGED	0	93	3.3
IVA - 32	STAGED	0	310	2.9
IVA - 33	FGR, STAGED	0	20	3.0
IVA - 34	FGR, STAGED	0	220	3.0
IVA - 35	STAGED	760	120	0.0
IVA - 36	FGR, STAGED	323	70	0.9
IVA - 37		0	330	4.0
IVA - 38	STAGED	0	269	4.6
IVA - 39	FGR, STAGED	0	198	4.0
IVA - 40		0	365	3.1
IVA - 41	SUBSTOICHIOMETRIC	10900	291	0.4
IVA - 42	SUBSTOICHIOMETRIC	44038	129	0.0
IVA - 43	SUBSTOICHIOMETRIC	151622	55	0.0
IVA - 44		22	152	2.7
IVA - 45		15	235	2.4
IVA - 46		475	194	0.7
IVA - 47		460	276	0.9
IVA - 48		15	316	4.4
IVA - 49		15	291	4.7
VA - 1		65	332	2.8
VA - 2		80	324	2.9
VA - 3		75	283	2.7
VA - 4		70	281	2.0
VA - 5		335	212	0.7
VA - 6		70	275	3.0
VA - 7		6	269	2.4
VA - 8		810	250	0.6
VA - 9		72	265	4.7
VA - 10		75	270	2.9
VA - 11		360	239	0.6
VA - 12		90	265	5.6
	COLORADO COAL			
VII - 1		90	953	2.7
VII - 2		60	1290	5.0
VII - 3		3900	643	0.5
VII - 4		60	820	3.6
VII - 5		60	881	6.6
VII - 6		950	910	1.1
VII - 7		120	1085	3.1
VII - 8		5000	675	0.6
VII - 9	SUBSTOICHIOMETRIC	14490	535	0.2
VII - 10	SUBSTOICHIOMETRIC	95627	707	0.0
VII - 11	SUBSTOICHIOMETRIC	149000	106	0.0
VII - 12	SUBSTOICHIOMETRIC	204000	74	0.0
VII - 13		70	1196	3.0
VII - 14		60	1368	6.0
VII - 15		2600	845	0.9
VII - 16		150	917	3.0
VII - 17		60	1102	6.1
VII - 18		2600	577	1.1
VII - 19		240	945	5.1
VII - 20		115	917	3.0
VII - 21		115	1042	5.9
VII - 22		60	854	6.2
VII - 23		40	657	3.0
VII - 24		930	643	0.9
VII - 25		375	774	2.8
VII - 26		100	1066	2.7
VII - 27		100	1327	6.2
VII - 28		150	1305	5.6
VII - 29		950	862	1.0
VIII - 1		80	1044	3.0
VIII - 2		100	1096	2.8
VIII - 3		80	1309	6.9
VIII - 4		2150	727	0.7
VIII - 5		150	786	2.9
VIII - 6		1700	539	0.7
VIII - 7		100	1143	7.0
VIII - 8		150	1086	3.0
VIII - 9		0	1299	6.4
VIII - 10	FGR	90	962	3.7
VIII - 11		100	1226	3.3
VIII - 12		105	896	3.1
VIII - 13		90	1014	6.3
VIII - 14		475	617	0.6
IXA - 1		120	1018	2.6
IXA - 2		30	911	5.1
IXB - 3	FGR	240	968	2.7
IXB - 4	FGR	190	868	2.2
IXB - 5	FGR	30	778	2.3
XA - 1		1700	968	0.9
XA - 2		130	917	3.2
XA - 3		30	869	3.1
XA - 4		100	1057	5.3
XA - 5		100	1207	6.4
XA - 6		425	986	2.6
XA - 7		60	990	2.8
XA - 8		150	965	2.9
XA - 9		120	1096	2.7
XA - 10		90	1135	3.0
XA - 11		100	1068	2.9
XA - 12		70	1249	6.2
XA - 13		75	1391	5.5
XA - 14		180	1129	3.4
XA - 15		150	1121	2.9
XA - 16		120	1035	2.4
XA - 17		60	1364	6.5
XA - 18		60	1396	6.7
XA - 19		180	1030	2.9
XA - 20		1600	679	1.1
XA - 21		120	1182	3.6
XA - 22		130	976	3.0
XA - 23		90	897	6.6
XA - 24		9500	415	1.2
XB - 25	STAGED	12900	252	1.6
XB - 26	STAGED	300	971	3.1
XB - 27	STAGED	1900	288	3.1
XB - 28	STAGED	100	990	6.4
XB - 29	STAGED	100	582	6.0
XB - 30	STAGED	180	935	3.0
XB - 31	STAGED	150	761	3.0
XB - 32	STAGED	360	590	2.6
XB - 33	STAGED	360	386	3.2
XB - 34	STAGED	910	389	3.7
XB - 35	STAGED	180	704	3.6
XB - 36	STAGED	960	412	2.0
XB - 37	STAGED	210	385	3.4
XB - 38	STAGED	360	329	2.6
XB - 39	STAGED	210	899	3.0
XB - 40	STAGED	90	898	4.2
XB - 41	STAGED	60	651	4.3
XB - 42	STAGED	90	430	4.2
XB - 43	STAGED	190	905	6.8
XB - 44	STAGED	240	768	5.4
XB - 45	STAGED	60	1039	7.3
XB - 46	STAGED	60	970	6.0
XB - 47	STAGED	60	771	7.2
XB - 48	STAGED	4400	331	1.3
XB - 49	STAGED	3100	352	1.0
XB - 50	STAGED	190	763	3.3
XB - 51	STAGED	140	496	3.6
XB - 52	STAGED	1200	435	3.6
XB - 53	STAGED	1200	395	3.2
XB - 54	STAGED	1130	493	3.6
XB - 55	STAGED	1100	477	3.6
XB - 56	STAGED	190	477	6.7
XB - 57	STAGED	4000	295	1.2
XIA - 1		120	1168	3.1
XIA - 2	STAGED	120	885	2.9
XIA - 3	STAGED	100	414	3.1
XIA - 4	STAGED	730	769	2.8
XIA - 5	STAGED	90	551	2.9
XIA - 6		3700	757	0.9
XIA - 7	STAGED	3900	467	1.0
XIA - 8	STAGED	120	315	1.3
XIA - 9	STAGED	2200	389	1.0
XIA - 10	STAGED	1200	315	0.9
XIA - 11		75	981	3.0
XIA - 12	STAGED	60	997	3.2
XIA - 13	STAGED	90	288	3.0
XIA - 14	STAGED	100	342	3.1
XIB - 1		90	1083	2.8
XIB - 2	STAGED	165	636	3.1
XIB - 3	STAGED	115	414	2.9
XIB - 4	STAGED	310	709	2.4
XIB - 5	STAGED	115	576	3.1
XIB - 6		2700	396	1.0
XIB - 7	STAGED	2000	634	2.9
XIB - 8	STAGED	1700	399	1.0
XIB - 9	STAGED	4030	401	0.9
XIB - 10	STAGED	3200	318	1.0
XIB - 11		165	657	2.4
XIB - 12	STAGED	140	601	2.9
XIB - 13	STAGED	190	436	3.2
XIB - 14	STAGED	190	360	3.2
XIC - 1		153	1096	3.2
XIC - 2	STAGED	430	673	2.9
XIC - 3	STAGED	810	295	2.9
XIC - 4	STAGED	1200	611	3.2
XIC - 5	STAGED	300	613	3.0
XIC - 6		4000	786	1.0
XIC - 7	STAGED	6400	338	1.1
XIC - 8	STAGED	6000	190	1.1
XIC - 9	STAGED	3500	385	3.4
XIC - 10	STAGED	4500	226	4.7
XIC - 11		125	940	2.8
XIC - 12	STAGED	960	396	3.0
XIC - 13	STAGED	900	257	2.9
XIC - 14	STAGED	260	364	2.9
XIIA - 1		100	1191	3.2
XIIA - 2	STAGED	75	933	3.4
XIIA - 3	STAGED	60	512	3.3

TABLE I.1 (CON'T) COMPARISON OF ALL PHASE I AND PHASE II WORK

TEST NOS.	COMMENTS	CO, PPM	NO, PPM	O2, %
XIIA - 4	STAGED	75	720	2.9
XIIA - 5	STAGED	150	567	3.1
XIIA - 6		3200	824	1.0
XIIA - 7	STAGED	1200	538	1.3
XIIA - 8	STAGED	1600	278	1.3
XIIA - 9	STAGED	2600	434	1.0
XIIA - 10	STAGED	2100	363	1.3
XIIA - 11		180	1327	7.3
XIIA - 12		200	1037	3.2
XIIA - 13		90	892	2.9
XIIA - 14	STAGED	80	506	3.0
XIIA - 15	STAGED	75	341	3.5
XIIA - 16	STAGED	60	540	3.4
XIIA - 17	STAGED	190	332	2.9
XIIA - 18		100	1002	3.0
XIIA - 19		60	1192	7.4
XIIA - 20		2300	765	1.0
XIIB - 1		65	1220	2.9
XIIB - 2	STAGED	330	914	2.7
XIIB - 3	STAGED	330	420	2.9
XIIB - 4	STAGED	60	865	2.9
XIIB - 5	STAGED	130	506	2.8
XIIB - 6		2400	871	0.9
XIIB - 7	STAGED	4300	576	1.1
XIIB - 8	STAGED	1400	303	1.0
XIIB - 9	STAGED	3600	524	0.6
XIIB - 10	STAGED	2150	304	1.1
XIIB - 11		120	1401	7.4
XIIB - 12		100	1216	2.9
XIIB - 13		200	1022	2.8
XIIB - 14	STAGED	140	631	2.7
XIIB - 15	STAGED	75	357	2.9
XIIB - 16	STAGED	55	607	3.0
XIIB - 17	STAGED	115	383	3.1
XIIB - 18		450	1046	2.8
XIIB - 19		30	1183	7.0
XIIB - 20		3900	748	0.8
XIIC - 1		60	1108	2.8
XIIC - 2	STAGED	330	875	2.6
XIIC - 3	STAGED	100	426	3.0
XIIC - 4	STAGED	120	726	2.8
XIIC - 5	STAGED	300	489	2.4
XIIC - 6		4400	726	0.6
XIIC - 7	STAGED	5000	408	0.7
XIIC - 8	STAGED	1000	326	1.0
XIIC - 9	STAGED	3950	420	0.8
XIIC - 10	STAGED	2800	238	1.3
XIIC - 11		200	1395	6.5
XIIC - 12		200	1172	2.6
XIIC - 13		100	1048	2.5
XIIC - 14	STAGED	500	549	2.4
XIIC - 15	STAGED	155	351	2.7
XIIC - 16	STAGED	240	569	2.4
XIIC - 17	STAGED	330	287	2.5
XIIC - 18		500	1062	2.9
XIIC - 19		180	1165	6.8
XIIC - 20		3730	714	0.8

Summary

The CO emission levels are dependent on O_2 levels, and in general CO is a function of O_2 — i.e., low O_2 levels (for lower NO_x emission levels) yield greater CO emission levels. However, CO is not as closely associated to NO but rather both CO and NO, although somewhat interdependent, are both a function of O_2. Operation of our coal fired unit below 1% O_2 yields substantial quantities of CO.

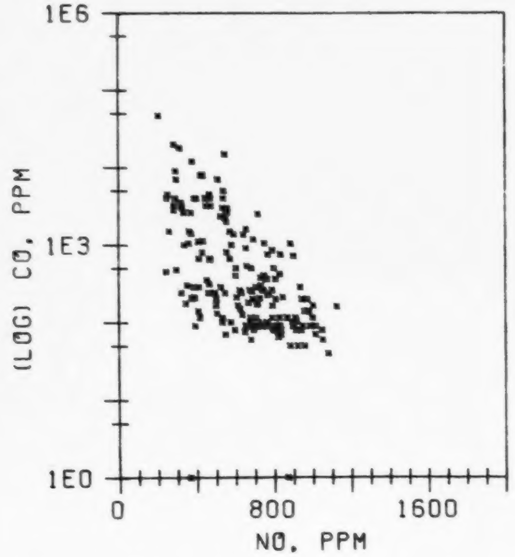

FIGURE I.1 CO VERSUS NO (OHIO COAL)

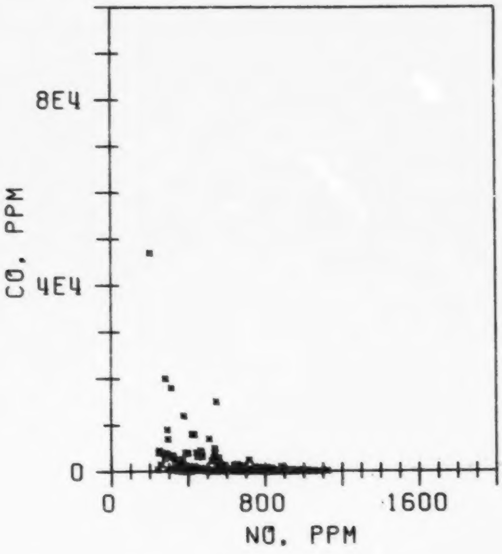

FIGURE I.2 CO VERSUS NO (OHIO COAL)

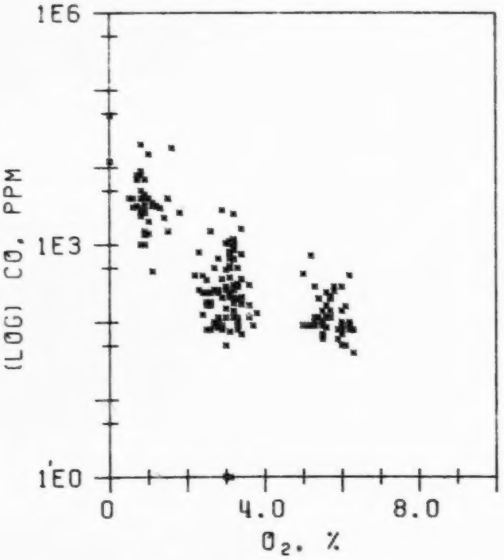

FIGURE I.3 CO VERSUS O_2 (OHIO COAL)

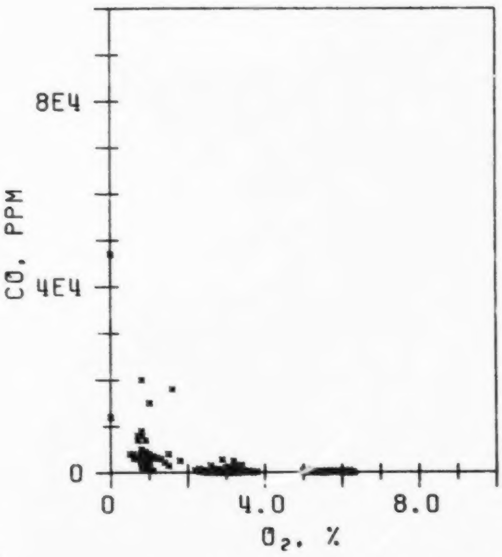

FIGURE I.4 CO VERSUS O_2 (OHIO COAL)

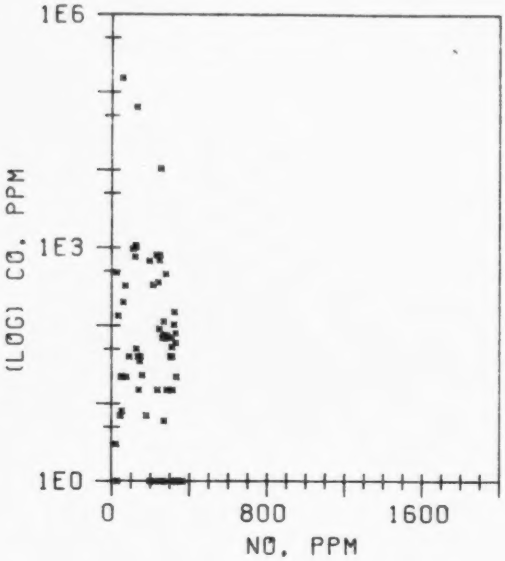

FIGURE I.5 CO VERSUS NO (NATURAL GAS)

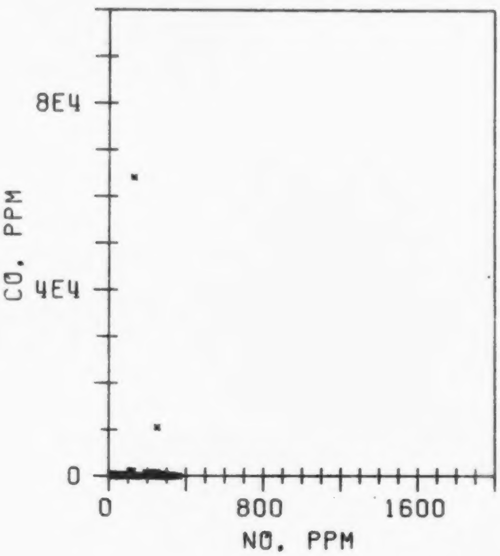

FIGURE I.6 CO VERSUS NO (NATURAL GAS)

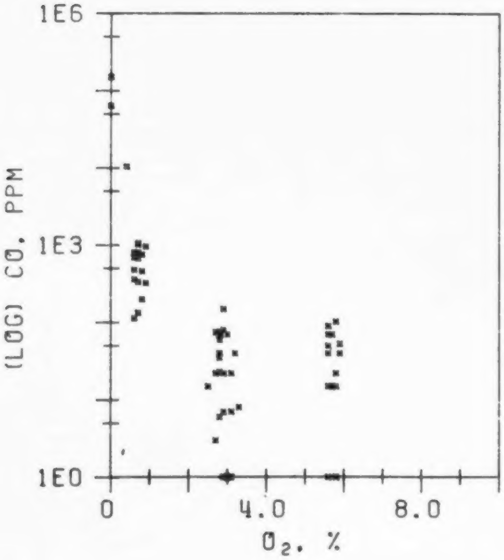

FIGURE I.7 CO VERSUS O_2 (NATURAL GAS)

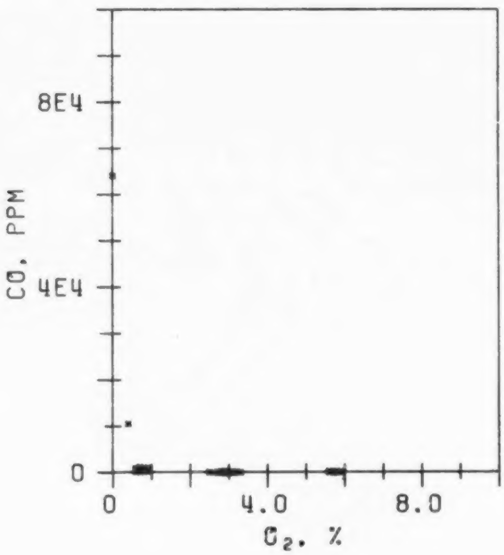

FIGURE I.8 CO VERSUS O_2 (NATURAL GAS)

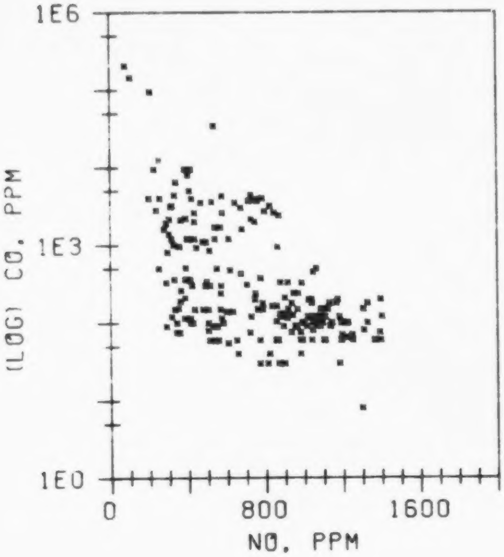

FIGURE I.9 CO VERSUS NO (COLORADO COAL)

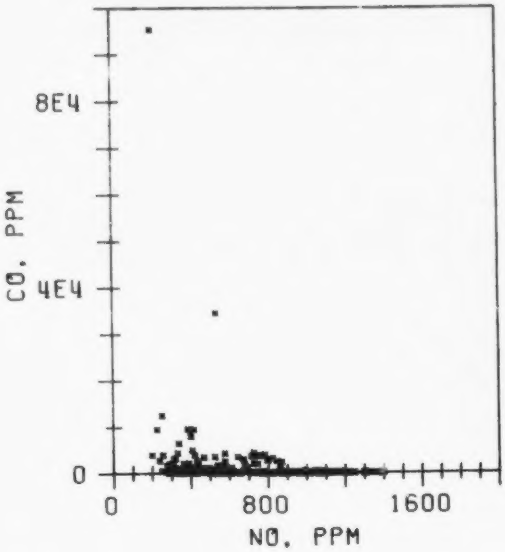

FIGURE I.10 CO VERSUS NO (COLORADO COAL)

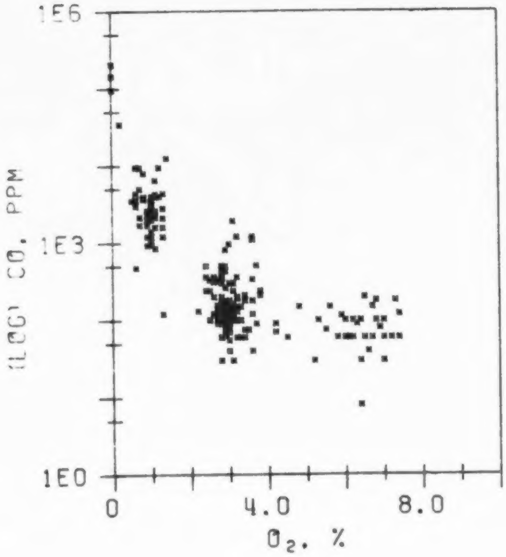

FIGURE I.11 CO VERSUS O_2 (COLORADO COAL)

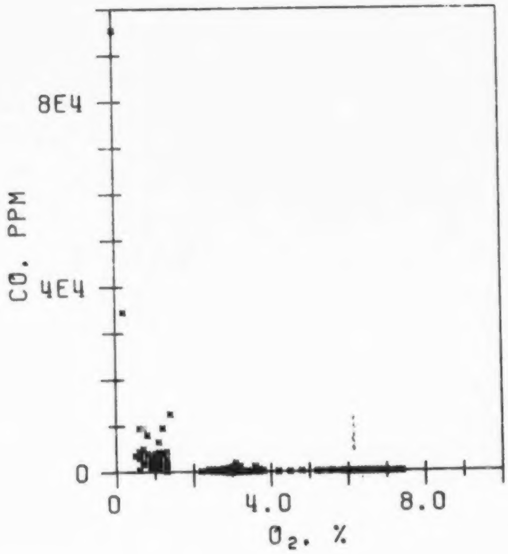

FIGURE I.12 CO VERSUS O_2 (COLORADO COAL)